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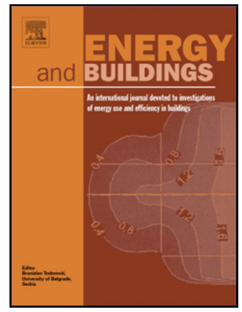

Title: Net zero-energy buildings in Germany: Design, model calibration and lessons learned from a case-study in Berlin

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Net zero-energy buildings in Germany: design, model calibration and lessons learned from a case-study in Berlin

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Highlights

- Energy performance of a net zero-energy building of the German Federal Government is shown
- The performance gaps between monitored and designed energy demand are verified.
- The measurements were used to calibrate a numerical energy model.
- For typical winter and summer weeks, the model was also validated against indoor temperatures
- The calibrated numerical model will be used for testing energy efficiency measures.

Abstract

The German Federal Government put its first net zero office building in operation in 2013 anticipating EU requirements for all public administrations to solely built “nearly zero energy buildings” from 2019 onwards. The two-storey building is situated in Berlin and has been designed for having an overall annual energy demand lower than the in-situ conversion of renewable energies. The paper shows the results of the first year of the operation. The overall annual electric usage is near to the expected value. Nevertheless, intensive monitoring showed differences between the expected and the measured electric usage in the areas of heating and domestic hot water (+172%), ventilation (-36%), lighting (-33%), equipment and auxiliaries (-14% and -13%, respectively), yield of the PV-system (+32%). A numerical model was created to investigate these deviations as well as to evaluate the impact of possible actions aimed at further improving the energy demand of the building. The model was calibrated with measured data, data from surveys, occupancy schedules, and validated by means of different indexes, among which the mean bias error (MBE). The MBE between monitored and simulated energy performance is below ±2% for all stated areas of energy usage. Analogously, the energy needs for cooling, monitored and simulated, as well as the trends of the indoor air temperature in both heating and cooling seasons, are in a very good agreement. In detail, the monthly MBE for the indoor temperature, in specific summer and winter periods and in the considered rooms, is below the threshold of ±5%, with values slightly higher (anyway lower than ±6%) only at the ground floor.

Finally, the paper shows that the reasons for the detected deviations in electric energy usage can mainly be related to the usage pattern of the building and to the occupants’ behavior. In order to ensure energy efficiency as high as planned, a suitable monitoring of the energy performance is fundamental. It enables the calibration and validation of tailored energy models to detect possible malfunctions as well as propose actions aimed at further reducing the energy usage of the building.

Keywords

Net zero energy buildings, building monitoring, calibrated energy model, energy efficiency measures, public buildings, commissioning.

1. Introduction and motivation of the study

In the framework of the last European directives concerning the energy performance of buildings, all EU member states enacted legislations in matter of a low-carbon future of the building sector with increasingly stringent predictions for the next years. Following the 2010/31/EU Directive [1], public administrations and institutions have to play a leading role in the field of energy efficiency in the building sector. The present European legislation was born under the 2002/91/EU Directive [2], which had an epochal impact by establishing for the first time common methodologies and targets for European activities in the field of energy efficiency of buildings. At national level, the EU member states transferred the European guidelines into national legislations, for instance in the case of the “Energieeinsparverordnung (EnEV) 2002” (Energy Saving Ordinance [3]) in Germany or the Legislative Decree 192/2005 in Italy [4]. Of course, following the development of new standardized calculation methodologies and advances in technology, national laws are continuously revised. In Germany, the development of laws followed the revision of the EnEV. Since 1 May 2014, the EnEV 2013 [5] is in force. Analogously, in Italy, following the legislative decree 192/2005, the following years saw the adoption of many regulations, and today the ones in force are the 90/2013 [6] law and the 26.06.2015 Ministerial Decrees [7].

The European 2010/31/EU Directive underlines the role of the public sector in spreading the culture of energy efficiency with new goals for the building sector. The new predictions concern both new and existing buildings, and Member States are solicited for reducing the cooling energy demand of buildings, of course, beyond the energy demand for the space heating. One of the most relevant new aspects introduced by the Energy Performance of Buildings Directive (EPBD) revision is the target of “nearly zero energy buildings”.. Member States in particular are requested to guarantee high-quality buildings with a minimized energy demand and mainly using renewable energies according to the following time schedule (Article 9 of the 2010/31/EU Directive):

- starting from January 2021, all new buildings shall fulfill the nearly zero energy standard;
- for new buildings owned and/or occupied by public administrations and authorities, the nearly zero energy standard is requested to start in January 2019.

Really, there is a noteworthy difference between “nearly” and “net” zero energy buildings (nearly ZEB and net ZEB, respectively). The first typology refers to a system of building/facilities that, during a certain period of one year, has balanced energy flows with regard to the energy demanded by the city and energy supplied to the public grid. It means that, annually, the building demands the same amount of energy locally converted from renewable energy sources. Differently, the definition of “nearly zero energy buildings is not uniquely fixed by the EPBD which in Article 2 (2) explains that “*the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*”. The definition is not absolute. In detail, a nearly zero energy building has to be defined at national level by taking economic issues, too, into account. By now, all over Europe, before net ZEB and nearly ZEB were developed, the so-called “cost-optimal balance” between energy costs and investments, based on the lifespan of technologies, has served as a guideline for the energy design of buildings. In 2012, the EU Commission Delegated Regulation No 244 [8] was enacted. It provides a comparative methodology for calculating cost-optimal levels, and this approach has been applied in several studies, e.g. in the document published by the Buildings Performance Institute Europe (BPIE) in Germany, Poland and Austria, which illustrates the procedure based on the proposition of case studies. [9].

A further international impulse for improving the European energy efficiency in buildings was given by the 2012/27/EU Directive [10]. According to the Directive, the Member States should make a strong effort in renovating their building stock. Indeed - and this is a quite well-known fact - the turnover rate of European buildings is quite poor. Therefore, proper strategies for funding and promoting the energy refurbishment of existing constructions are necessary in order to achieve a real sustainability of the whole building stock. The 2012/27/EU Directive provides for Member States to develop the definition of a "*long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both public and private*". Moreover, the Directive lays down that, since January 2014, central governments shall renovate at least 3% of the total floor area of their buildings, owned or occupied, in order to meet the national "minimum energy performance requirements". Once again, the exemplary role of the public sector is evidenced.

The study refers to a new "net" zero energy building built for offices of the German "Umweltbundesamt (UBA)", the Federal Environment Agency. The building, completed in 2013, is located in the south of Berlin. The so-called UBA 2019 was designed in order to be completely "green" and thus capable to compensate the very low energy demand with energy converted from on-site renewable energies. Solar systems for domestic hot water production and integration into heating systems, photovoltaic energy conversion into electricity, the use of low-enthalpy geothermal energy based on groundwater as a heat source for the heat pump and for cooling purposes were installed. Although the main objective of a net ZEB was achieved in the first year of operation (September 2013 – August 2014), some gaps between designed performances and measurements were revealed.

The main motivation of this study was to highlight the critical points that may affect the energy performance, expected and measured, of new buildings aimed at meeting the nearly zero energy standard. Indeed, a careful study, also for what concerns the mismatch between expectations and real behavior - suitably performed by means of careful investigations of each single energy system - might help to improve future choices thanks to the lessons learned. Moreover, a real understanding of the building behavior, also supported by a reliable numerical model, may allow feasibility studies and propositions of energy efficiency measures – presently under development - suitable for net-zero energy buildings. Indeed, once a model has been properly calibrated towards real energy data as measured, this could be a reliable starting tool for testing energy efficiency measures and evaluating their impacts on indoor comfort, energy demand, energy supply and general profitability. Presently, based on the results of this study, the increment in the use of electricity produced by photovoltaic systems and a higher seasonal balance between demand and conversion are under investigation by studying the profitability of electric storages and the installation of micro-wind turbines.

2. Nearly and net-zero energy buildings: state of the art of literature

First attempts to give a general definition of net and nearly zero energy buildings were proposed by Voss *et al.* [11] in 2011. Indeed, after the publication of the 2010/31/EC Directive, the term has been widely used without a clear definition, which - conversely – was absolutely necessary for implementing the concept of high-efficient buildings into the national energy codes of the EU member states. Voss *et al.* [11] underline that a net-zero energy building should completely compensate the energy demanded for the grid by the locally converted energy, privileging the use of renewable energies for the building's own necessities. If a net-zero energy building could be defined as in the aforementioned manner, the definition of a "nearly zero energy building", according to which the energy balance, with reference to a fixed observation period (usually one year), is not zero but higher, is quite ambiguous and means a net supply from the urban grid. A REHVA task force [12] proposed the following definition: Nearly net-zero energy buildings (nZEB) have a “national cost-optimal energy use of > 0 kWh/(m² a)”.

The reference lifespan for evaluating the energy flows of a net-zero energy building, according to several literature sources, is a conventional period of a solar year. During this time, energy demanded by the building should not overcome the energy converted from local renewable energy sources. Even if Marszal *et al.* [13] identify the annual balance as the most accepted measurement to evaluate energy flows in the present literature, other scientists/technicians suggest the whole lifecycle. Salomon *et al*. [14] and other authors underline that the “net” zero energy definition must be referred to buildings connected to the urban electricity system and, more in general, to energy grids. Thus, exclusively grid-connected buildings are commonly taken into account. Moreover, across the observation time, the same authors affirm that the energy balance between energy demanded by the grid and energy supplied should refer to a conventional period suitable to allow a global vision of the building behavior. The same concept was underlined by Sartori *et al*. [15], which focused on the role of the term “net”, saying that buildings generally are not energetically autonomous but that they use the grid as a "source" and "sink" to take and deliver energy. Finally, zero energy is evaluated according to a balance referred to a certain period as shown by the following Equation 1, clearly defined in many literature works, e.g. [15, 16].

$$net\ ZEB \Rightarrow Energy\ Balance: \left|weighted\ supply\right| - \left|weighted\ demand\right| = 0 \qquad (1)$$

In order to properly combine the on-site energy production provided to the grid and the energy demand, small-scale analyses as well are recommended. They refer to shorter observation periods to evidence possible problems, for instance, affecting energy grids, such as transmission capacity and/or voltage variations. This topic was discussed in [14].

A general overview of net-zero energy buildings, plus energy buildings and minus energy buildings is proposed in Figure 1. Here, energy demand and energy conversion are compared (Figure 1a) by showing that, in order to reduce the size of on-site renewable energy plants, the key factor is to minimize the final energy demanded by the building. The available solution is to improve the efficiency of both building envelope and active energy systems (Figure 1b).

Figure 1 here

With regard to the metrics of balance, Marszal *et al.* [13] identify some parameters beyond the pure “energy” quantities (e.g. „primary energy“, „end energy“, …), e.g. equivalent carbon dioxide emissions and energy costs. With regard to the energy uses that should be taken into account, the same authors identify those cited by the EN 15603 [17] standard and thus the energy demand for heating, cooling, ventilation, domestic hot water, humidification. For non-residential buildings, the energy demand for artificial lighting should also be evaluated.

Moreover, the energy included in building components might have a significant impact so that, recently, some studies proposed a methodological approach that extends the energy balance to the entire lifecycle. Cellura *et al*. [18] applied this new concept to an Italian building, born as a carbon-neutral architecture and then converted into a net zero energy house. The results of the life-cycle approach achieved are very interesting and motivations for also considering the embodied energy are provided. Analogously, Hernandez and Kenny [19] proposed a method for analyzing the building performance by taking the whole lifecycle into account.

Thus, the construction phase and the demolition process – beyond the useful operational lifespan – were taken into consideration.

The necessity of a lifecycle approach to evaluate the building sustainability, above all with regard to the future horizon of net zero energy buildings, is evidenced by Weißenberger *et al.* [20]. These authors, starting from the German ordinances that establish requirements for high energy-efficient buildings for the next years, show the increasingly higher share that the embodied energy will have, in the next future being lower than the energy demand during the operational phase. Indeed, the more and more stringent predictions in terms of thermal insulation, efficiency of active systems, local conversion from renewables cause a higher impact of both preliminary and demolition phases. Finally, the next goal is to extend the energy sustainability to the whole building lifecycle from the designing phase to the complete construction disposal. Hall *et al*. [21] proposed an overall overview of the lifecycle by identifying the reduction of embodied energy as a future challenge for engineers and architects. The study, referring to the Swiss experience, shows possibilities for transferring the lifecycle approach to the Minergie A standard. The study underlines the importance of the application of the net zero energy balance to clusters of buildings, so that optimizing energy grids could be a further possibility to improve and optimize the energy use.

With regard to the development and application of building regulations based on energy performance, Berry *et al*. [22] affirm the necessity of a clear definition of zero energy and zero carbon buildings. The authors largely reviewed the available literature and then suggest a regulatory definition to be translated into building codes.

With reference to both net zero energy and nearly zero energy houses, a large study of Thomas and Duffie [23] (i.e. sixteen case studies in New England) shows that the occupant behaviors may greatly affect the real energy performance of buildings. The authors underline that natural ventilation, extra-plugged devices and mechanical problems may affect the energy consumption and that the modelled predictions may significantly differ compared to the real energy measurements. These outcomes will also be confirmed for the case study investigated as shown in the following sections. The investigations of [23] are carried out based on the PHPP and EnergyGauge softwares. The Passive House Planning Package (PHPP) [24] has been developed by the Passive House Institute. It is compatible with the international ISO 13790 standard [25], even if further validations were also carried out based on comparisons with outcomes calculated with dynamic Building Performance Simulation (BPS). More information can be found in [26]. EnergyGauge, moreover, is a tool developed by the Florida Solar Energy Center [27, 28] based on the DOE-2.1 simulation engine [29].

The importance of monitoring the energy performance of buildings demand for having a clear base scenario suitable for supporting decision-making was underlined by Ferreira and Fleming [30]. They proposed a guidance for techniques suited to use measured data, in order to develop load profile indicators and to investigate potential energy efficiency measures. More than 80 buildings are proposed as case studies, characterized by various uses and quite different energy demands (commercial, offices, educational, hostels and health care facilities).

Still with reference to occupant behaviors, according to Section 10 of the 2010/31/EC Directive, the Member States should define the level of energy efficiency in order to achieve cost-optimality. Many related experiments have been done in continental and cold climates of Europe. For instance, Risholt *et al.* [31] proposed a nearly zero energy renovation of a detached single-family house in Norwegian climate, providing a double possibility, with energy efficiency measures applied to facades or to the whole building envelope. Obviously, the first approach required a more massive installation of renewables. In both cases, solar collectors and air-to-water heat pumps are identified as renewable systems. The renovation strategies in a feasibility study concerning qualitative and quantitative parameters mainly revealed a strong reduction of the energy demand for heating. The feasibility study also takes lifecycle costs and the homeowners' preferences into account. They turned out to be a key factor affecting the choice of energy efficiency actions.

The majority of the available literature in terms of net zero energy buildings concerns heating-dominated climates. Presently, few experiences are available for warm European countries, such as the Mediterranean region. An interesting question is proposed by Oliveira Panã *et al.* [32] who asked: “How low should be the energy required by a nearly zero energy building?” The authors answered that, with reference to warm climates and according to three scenarios (Portugal Regulations, Passive House Planning Package and predictions of the EN 15603 standard [17]), the primary energy demand should be lower than 60 – 70 kWh/m^{2}a considering the energy use for heating, cooling and warming of domestic hot water. Even if most experiences of net zero energy buildings are contextualized in cold areas, examples could also be designed in warm climates. Of course, in cooling-dominated countries, beyond a great attention to thermal insulation (expressed by means of the U_{values} of the components of the building envelopes), thermal capacity, low periodic thermal transmittance, low decrement factors, high mass and time-lag effects as well are required for the thermal envelope.

Ferrante and Cascella [33] proposed an example of net zero energy building for the South of Italy, by creating a comprehensive design of the building envelope (low values of the overall heat transfer coefficients and periodic transmittances, passive natural ventilation), active systems (heat pumps and variable refrigerant volume systems), renewable solutions (PV panels and micro-wind turbines). The results show that innovative technologies should be coupled to traditional solutions (as, for instance, protection by solar radiation by adopting massive envelopes).

Still with reference to warm climates that imply a significant energy demand for space cooling, Eshraghi *et al.* [34] proposed a study on a detached net zero energy family house in Iran. A wide combination of passive strategies (e.g. Trombe walls, thermal mass, solar screens), efficient equipment for heat generation (e.g. reversible adsorption heat pumps) and renewables (e.g. evacuated solar collectors and photovoltaic modules) are designed and evaluated according to technical and economic criteria. Annually, the building converts more energy than the demanded one, and thus the excess is delivered into the electricity grid. The design turns out to be feasible.

Another important topic concerns the environmental satisfaction of occupants in highly efficient buildings. Mlecnik *et al.* [35] proposed wide investigations in passive houses in Germany, Austria, Switzerland and in nearly zero energy buildings in the Netherlands. Surely, the comfort perception during the heating season is favorable. Nevertheless, barriers to the adoption of nearly zero energy buildings, e.g. by occupants and end-users, concern the summer comfort and the perceived air quality, above all with regard to the indoor humidity. The authors underline the necessity of a proper design of systems and equipment for the microclimate control including ventilation, noise protection and latent heat management. The building performance simulation (BPS) can be useful for designing technical solutions, as evidenced by [36, 37], also for optimizing zero energy buildings, by coupling EnergyPlus with a “ZEBO” user interface, for designers and architects. ZEBO is a highly promising tool being designed for warm climates. In terms of building performance simulation, Todorović [38] underlined the necessity of an overall and comprehensive design aimed at obtaining zero energy buildings for both new projects and renovations. Careful numerical simulations are powerful tools to investigate and manage the efficiency of building envelopes, active systems and to integrate renewable energy sources by determining their impact on the energy performance, occupant comfort, on operational costs, life cycle impacts and on the environmental sustainability.

In this context, by combining monitoring and dynamic simulation, the present paper evidences performances and criticalities when operating a real case study, the so-called UBA 2019 building, a net zero energy office recently built in Berlin, that hosts offices of the Umweltbundesamt (UBA), the German Federal Environment Agency. Division II 7 “Energy-Optimized Building” of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) within the German Federal Office for Building and Regional Planning (BBR) continuously monitors the energy performance of the UBA 2019 in terms of the energy demand of each use, the on-site energy conversion from renewables, indoor conditions. The BBSR accompanied the whole building process from the preparatory designing phase to the monitoring of the present operation [39].

Although the main objective of a net ZEB was more than achieved during the first year of operation, some gaps between designed performances and monitored ones were detected. Thus, by means of hourly energy simulations shared with the University of Naples Federico II (Italy), possible criticalities in the building use were identified by calibrating the numerical model on both the building design and the monitored data. As shown on the following pages, this allowed, to show some operational conditions differing from the designed ones. In the following sections, the building and its technical plants as well as the energy demand monitored and simulated, the on-site converted energy from renewables and the indoor temperature conditions will be presented.

The target of this study would be to prove the capability of calibrated energy performance of building models to find reasons and solutions for energy performances differing from the ones expected. Indeed, when a numerical model on real measurements is once calibrated, the BPS can be used for testing further energy efficiency measures and for optimizing the use of renewable energy.

3. Presenting the building case study

UBA 2019 was designed and built in Berlin (2009-2013) as the first net zero energy building of the German Federal Government, and is thus more efficient than the requirements of the European 2010/31/EC Directive (i.e. “nearly” zero energy building) call for. During the designing phase, there was a synergic participation of various professionals to set all wheels of energy efficiency in motion and thus to achieve a) efficiency of the building envelope, b) efficiency of all active systems for microclimatic control and artificial lighting, c) on-site energy conversion from several renewable sources. The building concept was oriented toward the “Gold” classification of the Assessment System for Sustainable Building (“Bewertungssystem Nachhaltiges Bauen BNB”) [40], the German sustainable/green building rating tool of the German Federal Government (for Federal buildings).

The building has a compact square shape (Figure 2). The gross dimensions - width and length - are 25 m, although the east-west facade has a longer aspect, due to the anterior porch on the south exposure. Most offices are for one person, the building also has three meeting rooms that can be connected with each other. Other spaces are used for services (for example kitchen and toilets), technical rooms and common areas. In Figure 3, the ground and first floors are shown.

Figure 2 here

Figure 3 here

With regard to the thermo-physical properties of the building and in order to reduce the energy need for heating (e.g. cooling can be almost produced without energy costs by using groundwater and natural ventilation), the envelope structures were strongly thermally insulated by large thicknesses of cellulose fiber. The composition of the thermal envelope is the following:

- External wall: the overall thickness is 0.46 m (including 36 cm of cellulose insulation). On the inner side, there is an OSB (i.e., Oriented Strand Board) plane with a coating of drywall. Externally, a breathable wooden fiberboard is installed. The overall U_{VALUE} is 0.12 W/m^{2}K.
- Flat roof: the overall thickness is 0.96 cm, with insulation by cellulose fiber of 53 cm. The structural elements are wooden box beams with a thickness of 28 cm. On the outer side, there are 10 cm of mixed sand, gravel, chippings with extensive sedum vegetation. Other intermediate layers are two OSB boards, a vapor barrier on the inner side, a waterproofing layer on the external side. The overall transmittance is around 0.05 W/m^{2}K.
- Floor on the ground: the wooden box beams are insulated with 12 cm of polyurethane. On the inner side, a light concrete layer of 6 cm is used as a substrate of the parquet pavement. The overall thermal transmittance is 0.09 W/m^{2}K with a total thickness of 0.49 m.
- Windows and skylights: they are triple-glazed systems with certified overall U_{VALUES} of 0.70 and 0.86 W/m^{2}K considering the weighted average of the glazed part and the frame (i.e. U_W). The windows have wooden frames with a metallic external cover protecting from atmospheric agents., They are equipped with shading systems (horizontal slats). The shadings are located externally to the second glass. The third glass can be opened separately, allowing the windows to be two- or three-glazed.

The U_{VALUE} of the partition between office and bathroom is 0.26 W/m^{2}K, while the curtain wall separating two contiguous offices has a thermal transmittance around 0.66 W/m^{2}K.

During the last phase of construction (July 2013), a blower door test was performed in order to verify the air tightness of the building. As established by current methodologies, the tests were carried out by a series of under-pressure and over-pressure measurements, referring to the overall building volume, at a differential pressure of 50 Pa. The measured rates of air change per hour (ACH), at a differential pressure of 50 Pa (i.e. n_{50}), ranged between 0.30 h^{-1} and 0.35 h^{-1}.

By averaging the value, the certified ACH was 0.33 h^{-1}. It should be noted that the reference threshold for passive buildings was ≤ 0.60 h^{-1} (Passivhaus Institut, http://www.passiv.de/). Finally, UBA 2019 shows a certified (November 2013), satisfactory air tightness.

With regard to indoor microclimatic control, in-room capillary radiant systems and handled ventilation air (Figures 2b and 2d) allow to heat and cool the building. Capillary tubes are embedded in the external walls for heating and in the partition walls for cooling. A water-to-water geothermal heat pump provides the heating energy.. Groundwater is used indirectly by passing a heat exchanger for cooling the building. In each office, dew point sensors are installed, in order to prevent condensation. Therefore the summer comfort is provided by means of free cooling, by requiring solely auxiliary energy for pumping.

The preference of passive technologies and low-energy cooling concepts, such as the one proposed here, are the great challenge for future building activities, as recently reviewed by F. Pacheco Torgal [43].

The mechanical ventilation system - large in order to handle an amount of outdoor air enough for achieving the comfort category II according to the EN 15251 standard [44] in each room - is equipped with a sensible flat-plate heat recovery system aimed at reducing the ventilation load.

A set of renewable energy systems is installed. Indeed, beyond the heat recovery from the exhaust air, the water-to-water heat pump uses the ground source (i.e. the groundwater) in order to increase the temperature at the evaporator source in wintertime. Moreover, the same groundwater allows the cooling of the building during the entire year. The building is also equipped with a solar thermal energy system, with an overall solar collector area of 11 m^2 and two thermal heat storages (puffers), each one 970 l. The inclination angle of the solar collector is 37°, with a slight deviation around 8° from the south exposure.

A large photovoltaic system is installed on the building roof. In order to reduce the system visibility and to maximize the system power and production (with the reduction of mutual shadows among the arrays), a sub-horizontal inclination with a tilt angle lower than 10° was preferred. The total installed capacity according to Standard Test Conditions (STC) is 66.33 kWp. The designed specific conversion is 790 $kWh_{ELECTRIC}$/kWp. The overall area of photovoltaic modules is around 391 m^2.

Table I here

Table I provides the main boundary conditions about building geometry, building envelope, HVAC systems and installed renewable energy sources. As said, the building was completed in 2013. It costed around 4'200 millions of euros (net), and this corresponds to specific costs per gross floor area of about 3'325 €/m^2. This price takes all building categories identified by the German DIN 276 and DIN 277 standards into account, i.e.:

1. "Grundstück" (→ costs associated to the building permit and the construction yard);
2. „Herrichten und Erschließen" (→ preliminary and infrastructural works);
3. „Bauwerk – Baukonstruktionen" (→ construction costs for architectural works)
4. „Bauwerk - Technische Anlagen" (→ constructions cost for systems and general equipment);
5. „Außenanlagen" (→ external equipment, structures and devices);
6. „Ausstattung und Kunstwerke" (→ eventual special equipment and works of art);
7. „Baunebenkosten" (→ auxiliary costs).

Of course, not all buildings are concerned by costs for each one of the aforementioned categories. Moreover, it should be noted that UBA 2019 is provided with significant external equipment, such as roofed parking spaces for bicycles, a barrier-free infrastructure and special outdoor facilities.

With regard to the common categories of costs, and thus categories 3 (architectural works) and 4 (indoor technical equipment), the costs of UBA were 2'350 €/m^2. In Germany, an average value for the analogous cost index, with reference to highly equipped office buildings, is around 1'730 €/m^2. Finally, UBA 2019 had extra-costs of about 35 – 40% compared to a similar building, but it should be noted that, at the time of building design and construction (2009-2013), the costs of technologies for highly efficient buildings were much higher than now (Summer 2016). In order to understand it, it is enough to note that, five years ago, a standard price for a photovoltaic system was around 3'500 €/kW_p, while today this value is between 1'300 – 1,500 €/kW_p. The overall energy concept of the building is provided in Figure 4, where the main energy vectors and sources are schematized with reference to the energy supply.

Figure 4 here

3.1 Building modelling

Transient energy simulation, when validated based on proper calibration, compared with monitored data is a powerful tool to understand gaps between design and operation, inefficiencies of building systems as well as to test energy efficiency measures aimed at improving building performances. Methods and protocols for calibrating energy models were developed by FEMP and ASHRAE [45, 46 and 47] and these are applied in our investigations. The numerical software used is EnergyPlus 7.2.0 (https://energyplus.net/testing) [37]. A number of authoritative studies is available at the website of the U.S. Department of Energy, where an entire section deals with testing and validations. These tests concern building envelope, HVAC systems, particular heat transfer phenomena (i.e. interzonally or through the ground) as well as single systems and equipment (heat pumps, chillers, boilers, fans, pumps and so on). Generally, the outcomes are quite satisfactory, evidencing the reliability of the program (in previous studies also used to investigate the performances of net or positive energy buildings as for instance by Bojic *et al*. [48] with reference to the Serbian climate). In literature, this engine was used for single studies - referring to houses [49, 50], educational buildings [51, 52] and offices [53, 54], health care facilities [55, 56] - and also for larger investigations, for instance in order to analyze how much the radiative characteristics of the envelopes of a set of buildings may affect the energy performances of each other [57].

In our study, in order to define the building geometry and the general boundary conditions of the several functions of the building (i.e. office rooms, common spaces, kitchens and services), DesignBuilder 3.2.0 [58] was adopted, and this is a very appreciated interface of EnergyPlus. In Figures 5 and 6, some details of the real building and the modelled one will be compared, and the main data affecting the energy simulation, such as the climate boundary conditions and other relevant parameters, will be reported in Tables I and II.

Figure 5 here

Figure 6 here

Materials and constructions were accurately defined in EnergyPlus for reproducing the real thermal-physical properties of the building envelope, such as provided by the design documentation (i.e. layers orders, the materials' thermal conductivity, density, specific heat, etc., defined to the best of the authors' knowledge, even if some minor approximations might concern specific issues). More in detail, every time documentations were available, and this is the most common case, we have defined exactly the same building materials and entire components. Finally, for what concerns the opaque and transparent building envelopes, the modeled components are those described in the bulleted list of the general introduction of the section 3 (Presenting the building case study) and whose peculiarities reported in Table I. The same table summarizes also the typology and thermo-dynamic parameters (e.g., energy efficiency ratio, coefficient of performance, efficiencies) of active energy system for the microclimatic control and photovoltaic plants, whit description reported in the same introduction of the section 3.

About the schedule of use of shading systems of windows, in order to simulate as reliable as possible the occupants' behavior and the building use, we have established that these can be used only during the diurnal hours, mainly in the central part of the working day. In particular, in EnergyPlus we have defined a control schedule that activates the solar screen only for incident solar irradiance on windows higher than 120 W/m^2.

Moreover, systems and equipment for endogenous appliances and lighting were accurately planned, also by defining suitable schedules of use when available, or adopting conventional profiles for office buildings. In particular with regard to the modelling of artificial lighting, dimmable systems were defined, in order to integrate the natural daylight, when necessary, by means of a lux-control command (EnergyPlus field: "*Daylight:Control*"). For what concerns the electricity demand for lighting, of course the occupant' behavior and the real occupancy are determinant. We have chosen default values for new office buildings, and thus, according to typical schedules, illuminances levels (time-averaged along the use) equal to 500 lx (office rooms), 200 lx (WC and kitchens), 150 lx (technical room). These values are ensured by a lux control method which integrates daylight and artificial lighting. The high flexibility of EnergyPlus allows modeling both equipment and their modality of use during day, week, season, and so on. Various yearly profiles of use have been defined, depending by the room destination (office, kitchen, bathrooms, circulation, technical rooms), with variable power density (from 2 to 10 W/m^2) and different schedules along the day. For instance, technical rooms have a constant use of plugged powers, offices have the highest use in the middle of morning and evening, a peak in the use of kitchens there is between 12.00 and 13.00. More than 550 'compact schedules' have been defined in EnergyPlus, starting from the ones proposed, for each destination, by the program interface DesignBuilder [58].

Concerning the modelling of the HVAC system and the ventilation devices, including the heat recovery, the groundwater heat pump, the solar thermal system and the photovoltaic electric generators, the IDF generator of EnergyPlus was directly used. About the numerical model, EnergyPlus allows to choose different methods for the heat balance algorithm, among them the “conduction transfer functions” (CTF) and the “conduction finite difference” (ConFD). More rarely, other methodologies are adopted, such as the “combined heat and moisture finite element” algorithms (HAMT) [37].

The energy programs for the building performance simulation (such as EnergyPlus, which neglects the air thermal capacitance) provide the thermal zone loads by means of Equation (2), in which the thermal energy supplied by heating systems [37] should balance the sum of heat losses and gains.

$$-Q_{HVAC} = Q_{LOAD} = \sum_{i=1}^{Nsj} \dot{Q}_i + \sum_{i=1}^{Nsurface} h_i \cdot A_i \cdot (T_{si} - T_z) + \sum_{i=1}^{Nzones} m_i \cdot c_p \cdot (T_{zi} - T_z) + m_{inf} \cdot c_p \cdot (T_{ext} - T_z) \qquad \text{(Eq. 2)}$$

In Equation 2:

T_z is the indoor air temperature,

$\sum_{i=1}^{Nsj} \dot{Q}_i$ is the sum of convective internal loads,

$\sum_{i=1}^{Nsurface} h_i \cdot A_i \cdot (T_{si} - T_z)$ is the convective heat exchange resulting from the zone surfaces,

$\sum_{i=1}^{Nzones} m_i \cdot c_p \cdot (T_{z,i} - T_z)$ is the heat transfer due to the interzonal air mixing,

$m_{inf} \cdot c_p \cdot (T_{ext} - T_z)$ is the heat transfer due to the outdoor air infiltration.

The heat transfer resulting from building components affects the indoor surface temperatures (T_{si}) and thus the convective heat exchange between building surfaces and indoor air, as evidenced in Equation 3

$$-q''_{conv} = q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{sol} + q''_{ki} \qquad \text{(Eq. 3)}$$

in which q''_{LWX} is the long-wave radiation heat transfer among surfaces, q''_{SW} is the short-wave radiation among surfaces and light emitters, q''_{LWS} is the long-wave heat transfer among surfaces and emitters, q''_{sol} is the solar flux, q''_{ki} is the heat conduction through the building envelope. This last can be solved by means of different approaches (CTF, ConFD, HAMT). According to the conduction transfer function expressed in Equation 4 [59], the heat flow q''_{ki} through the building envelope is calculated, and it is necessary in order to solve Eq. (3),

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} \dot{Z}_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Psi_j q''_{ki,t-j\delta} \qquad \text{(eq. 4)}$$

With reference to Equation (4), q''_{ki} is the inside conduction heat flow per unit area (i.e. q/A), T are temperatures, "i", and "o" identify the inner and outer faces of the structure respectively, t is the current time step, Z, Y and Ψ are the inside, cross and flux CTF coefficients.

A similar formulation concerns the outside heat conduction. The methodology adopted for the CTF resolution is the state space representation, formulated in [59, 60] and based on the use of matrix algebra. In a first step, the building component is discretized into a discrete numbers of nodes to establish a mathematical domain. The energy balances should solve a set of, ordinary and first order differential equations. In general, regarding the heat transfer process characterized by state variables (e.g. the nodal temperatures), inputs (e.g. indoor and outdoor air temperatures, solar radiation) and outputs (e.g. just the heat flows), the space state representation starts from the systems of the Equations 5 and 6.

$$\begin{cases} \dfrac{d\mathbf{x}}{d\tau} = \mathbf{Ax} + \mathbf{Bu} & \text{(eq. 5)} \qquad \text{Eq. 5} \\ \mathbf{y} = \mathbf{Cx} + \mathbf{Du} & \text{(eq. 6)} \qquad \text{Eq. 6} \end{cases}$$

In the aforementioned mathematical system, "**x**" is the vector of space state variables, "**u**" is the vector of inputs, "**y**" is the vector of outputs, "τ" is the time. **A**, **B**, **C** and **D** are matrixes of constant terms, based on which the CTF coefficients are calculated. The state space representation is a very powerful tool: indeed, it allows to evaluate heat flows without requiring to determine nodal temperatures. Some authors of this paper summarized the whole procedure in [61], where the reliability of the method was tested by means of comparisons to finite volume methodologies also with the aim to find a new methodology in commercial software to implement thermal bridges for the dynamic energy simulation of buildings [62, 63]. Furthermore, the reliability of the method was tested [64] based on results achieved by means of the state space method and those derived from the analytical solution, leading to consistency and lower computational costs. In the same directions, the state space representation was found accurate and suitable for engineering applications by [65].

The CTF method is very powerful, because the formulation correlates the heat flux at one face of building element to the current and some of the previous temperatures (at both inner and outer surfaces) and to the previous values of heat flows. Power and elegance of the method are due to the fact that, by adopting the matrix algebra, the nodal temperatures can be neglected, so that no spatial discretization of walls is necessary and the thermal field should not be completely determined based on the envelope [37]. Finally, the method is fast and accurate, even if very massive buildings may show criticalities. With regard to the low-temperature radiant heating and cooling, such as the systems installed in the walls of UBA 2019, two dedicated models of EnergyPlus have been used. More in deep, the resolution of a construction with internal sources require an extension of time series solutions, in order to include the heat source and for obtaining the internal temperature and the surface temperature of the building component. The CTF are integrated with QTF (heat flux transfer functions), also based on the state space representation, as detailed in [66], to calculate the time series coefficients. Radiant panels are considered as BITES (building-integrated thermal energy storage), and it is assumed that the temperature of the embedded system along its length is constant within a time step. The internal source is considered as heat exchanger and, for solving the amount of energy transferred from the fluid to the solid layer, the NTU method (number of time units) is used [37, 66].

4. Results and discussion

4.1 Simulating building design and building performance

During the planning phase, the adopted numerical code was TRNSYS [67], that allowed the investigation of energy flows of the complex system 'building / active energy plants' by performing hourly energy simulations with an hourly time step. In our study, we have used EnergyPlus [37]. The main results of a comparison between the results from the different energy models, are shown in Table III. In particular, with reference to an annual basis, the building energy model, based on the hourly energy balances, revealed energy demands for each use very well correspondent to the ones expected according to the building design. In this context, it should be noted that the designers, also aided by energy experts, already provided a transient energy model of the building, in order to have a tool for optimizing the energy performance. As largely discussed in the previous literature, indeed, simplified tools, such as the ones used for energy labelling and/or energy certifications, do not allow reliable energy behaviors but merely conventional energy demands for few energy uses (heating, DHW, artificial lighting).

Table III here

According to the design concept (Table III), the building only requires electric energy without in-situ combustion of fuels, and the overall energy request is lower than 44'500 $kWh_{ELECTRIC}$. The gross building floor area is 1'264 m^2, the net one is 1'000 m^2 (1'178 m^2, including the inner walls) and this last value has been considered for calculation. Therefore, the specific energy demand is around 37.7 $kWh_{ELECTRIC}/(m^2a)$ and it means a specific primary energy demand of around 96.7 $kWh/(m^2a)$ if the average primary energy factor of the German power system, which is 0.39 $Wh_{ELECTRIC}/Wh_{PRIMARY}$ according to [68], is taken into account. Similar results, as shown in Table III, have been calculated by means of the BPS. Regarding the photovoltaic system, an annual electric conversion of 52'461 $kWh_{ELECTRIC\text{-}AC}$ was expected by means of the system design performed with PV*Sol [69]. This design value was compared with hourly simulations carried out with EnergyPlus, and the obtained energy conversion was 53'079 $kWh_{ELECTRIC\text{-}AC}$ (+1.2% compared to the PV*Sol system design). The monthly values are reported in Figure 7.

Figure 7 here

Also in this case a comparison between the expected performance at the stage of building design and the simulated one has been considered necessary. Indeed, two different programs have been used (PV*Sol during the design, EnergyPlus for our investigation) and the first thing to do is a suitable verification of outcomes, in order to assure a good agreement of energy models. Thus, a suitable correspondence for what concerns input data and calculations has to be verified, before proposing a calibration of the new transient and tailored energy model against measured data. It should be noted that EnergyPlus operates by considering solar radiation, air temperature, air mass, sky conditions and all other climatic parameters related to the city of Berlin, as provided by the IWEC hourly weather file. The Berlin IWEC file is the reference year, built according to methodologies developed by the ASHRAE [70].

With reference to the energy demand for cooling, as aforementioned, this is supplied by using, through an heat exchanger (water-to-water heat exchanger, $\eta = 0.80$), the cool groundwater already used for the heat exchange at the evaporator of the water-to-water heat pump during the heating operation. Therefore, with reference to this energy use, no electric or primary energy is required, with the exception of the operation of pumps and fans.

According to the building design, the cooling energy need (i.e. thermal energy) is 27'562 $kWh_{THERMAL}$ and it means a specific value of around 23.4 $kWh_{THERMAL}/(m^2a)$. Conversely, according to the energy simulation carried out by using EnergyPlus, the annual energy demand is 27'721 $kWh_{THERMAL}$ (i.e. 23.5 $kWh_{THERMAL}/(m^2a)$). Thus, the percentage difference is around +0.6%, by taking into account the efficiency of the heat exchanger. This result as well is fully acceptable in order to consider the building simulation model built in EnergyPlus well correspondent to the expectation of the designing phase.

However, a larger error characterized the performances of the solar thermal system. Indeed, according to the building design, it should provide around 3'800 $kWh_{THERMAL}/a$, while the energy simulation in EnergyPlus, also having accurately defined the whole equipment, provides a much lower thermal conversion by solar sources. In further studies, this will require some further investigations.

4.2 Building use: monitoring the building

According to the aforementioned demonstrative role of the public hand, beyond a building design appropriate for the optimization of the building performance, also the operational phase of the building use assumes a central role, because the occupant behavior highly affects the energy demand. Finally, together with other many public buildings, the UBA 2019 net zero energy building in Berlin is fully-monitored by the BBSR Division II 7, that collects, records and analyses the main energy flows for every use as well as the indoor microclimate. UBA 2019 is equipped with a full monitoring apparatus, in order to have continuous metering of all energy flows, for each use. In detail, there are installed 83 electric meters, 26 heat counters, 4 meters for cold and hot water. Moreover, an outdoor weather station, constituted by 10 sensors, measures the outside air temperature and relative humidity, wind direction, wind speed, global solar radiation, CO_2 concentration, illuminance.

As the UBA 2019 is also used as a kind of "living lab", a parallel system was also installed for having measured trends and values characterizing the indoor microclimate. This is composed by fixed and mobile systems. In particular, the indoor air temperature is measured in each room and, for four representative spaces, further 18-27 sensors are installed for measurements concerning the thermal comfort, the indoor air quality (CO_2 concentration), people presence, illuminance and lighting level, status of use (e.g. window contacts, use of shading devices). Moreover, the mobile system - that can be installed for some days in every space of the building - measures the thermal comfort by means of 8 sensors as well as the presence of persons. Beyond the aforementioned monitoring apparatus, characteristic of a living lab, other “hidden” sensors-actuators are used for the normal operation of all devices and technical equipment of a building equipped with home automation controllers. A scheme of the monitoring concept is proposed in Figure 8.

Figure 8 here

4.3 Comparing building energy requests and predicted values of the design phase

Actually, the measured data revealed some gaps between the expected building energy demands and the energy measurements. A related comparative overview is reported in Figure 9. The outcomes concern a period of one year, namely from September 2013 (start of building operation) to August 2014.

Figure 9 here

The high differences in some energy uses (e.g. electric energy demanded for heating, lighting, office equipment and ventilation) induced the authors to think that the occupant behaviors as well as the rate of occupancy, have been different from the expected ones. More in detail, the gaps between measurements and designed energy performances revealed much higher energy requests for the production of heat (space heating and domestic hot water). More in detail, a thermal need of 23’642 $kWh_{THERMAL}$ (i.e. 10’607 $kWh_{THERMAL}$ for space heating, 13’035 $kWh_{THERMAL}$ for the DHW) was presumed during the design phase. The expected solar integration would be 6’620 $kWh_{THERMAL}$, so that, by proportionally assigning this covering to the two energy uses (for clarity reasons), it implies:

- the net energy need for space heating: 7’637 $kWh_{THERMAL}$,
- the net energy need for domestic hot water: 9’385 $kWh_{THERMAL}$.

In terms of electric energy, by considering the expected average coefficient of performance of the Heat Pump of 3.9 $Wh_{THERMAL}/Wh_{ELECTRIC}$, the aforementioned needs would require 4’364 $kWh_{ELECTRIC}$ (i.e. 1’958 $kWh_{ELECTRIC}$ for space heating, 2’406 $kWh_{ELECTRIC}$ for DHW).

However, the measured electric request for the space heating was quite higher, 10’037 $kWh_{ELECTRIC}$ for the same period compared to the expected value of 1’958 $kWh_{ELECTRIC}$. The electric demand for heating, starting from the measured value, was calculated based on the total energy requested by the Heat Pump, including the pump of the ground-coupled side and then by considering the incidence of the heating need compared to the sum of heating and domestic hot water requirements. The contribution of the solar thermal system is quite negligible. The average coefficient of performance of the Heat Pump is close to the expected seasonal value, i.e. 4.0 $Wh_{THERMAL}/Wh_{ELECTRIC}$.

Moreover, the measured electric request for the production of hot water was much lower than the expected one. Indeed, it was estimated an annual electric demand equal to 2’406 $kWh_{ELECTRIC}$ (by considering the integration in energy supply by means of the solar system and by adopting the same calculation method above described), while the real energy requested is around 1’848 $kWh_{ELECTRIC}$. This outcome should also consider that the monitoring revealed a not proper work of the solar system, at least until spring 2014. Still regarding the electric energy demand for the production of hot water, a much lower use of DHW, i.e. 36.3 m^3/year compared to the design value (193 m^3/year), has been observed.

Comparing monitored data to expected ones, other relevant differences concerning the electric energy demand for auxiliaries (-13.2%), for ventilation (-36.2%), for artificial lighting (-33.3%), for office devices (-14.0%) were registered. A summary is shown in Figure 9.

In terms of energy efficiency of the building sector, the gap between expected energy demands and measured ones is a very actual topic. Indeed, the role played by the occupants may significantly affect the energy demand of a building, such as already established by the EN 15603 standard [17]. Concerning energy diagnosis and feasibility study, this document, proposes the use of "tailored ratings" (with boundary conditions defined according to the real building use) instead of asset ratings, based on input data derived from a conventional lifecycle of buildings. The issue is discussed by Martincig *et al*. [71], who highlighted the role of occupants in reducing the gap between real building performance and expected behavior by involving users in a new synergy among design, management, use of edifices. Beyond the energy demand, analogue issues concern the thermal comfort, as expected and perceived. The same theory forms the basis of the adaptive model for comfort, ANSI/ASHRAE 55/2010 [72] or of the EN 15251 standard [44], according to which the degrees of freedom of occupants play a great role for life satisfaction. The gap between expected performance and energy consumption was also studied by Andersen et al.[73], who in the context of five case studies tested stochastic models of occupants' behavior simulated from literature data against measurements of energy demand. According to Majcen *et al*. [74], the so-called performance gap is mainly due to discrepancies in modelling U_{values}, indoor temperatures and ventilation rate, while the internal loads and number of occupants have a limited impact.

With regard to buildings located in South Germany, Calì *et al*. [75] identified a great performance gap between the real and expected energy performance of buildings, by identifying the occupants' behavior as a main reason, even if a great role was also played by installation and malfunctioning active energy systems. According to our investigation, also in the case of UBA 2019, the significant differences between expected and measured energy performances were due to the occupants' behavior and to the patterns of use of the building. These aspects will be deepened in the next section.

5. Calibrating the transient energy model: methodology and reliability

The differences among monitored energy request and expected values suggested the definition of a new building model, calibrated according to the present building operating conditions and patterns of use, in order to verify reasons and motivations of differences in energy performances. The following causes of the aforementioned differences in energy demands were identified:

- insufficient occupancy of the building, mainly during the first months of operation, and thus a lower use of artificial lighting, office equipment, ventilation, especially with regard to the meeting rooms at the first floor.
- lower use of the heat recovery in the ventilation system compared to the expected one (also operating with lower efficiency). Probably, it was bypassed in many hours;
- much higher natural ventilation loads, due to a more frequent opening of windows, also because of the indoor sensation of over-heating. Indeed, the air-tightness of the building has been verified by means of the above-described blower-door test, and thus the only possible reason of the additional air exchange is the opening of windows, even if a suitable indoor air quality (Category II according to EN 15251) is guaranteed by the mechanical ventilation system. It should be noted that the ventilation

system is equipped with heating and cooling coils, in order to avoid discomfort related to the supply of ventilation air;
- higher indoor set point for heating. In each single office, the occupants can modify, up to ± 3 K, the general set point for the indoor air temperature, by acting on the "in-room" thermostats. This explains both the higher energy demand for heating and the increment of natural ventilation.

With reference to the cooling need, it is noteworthy to underline that the capillary radiant system in an attenuating mode, may also work, in wintertime because of hyper-insulating the building envelope. Indeed, the space cooling can be almost achieved without energy costs by natural ventilation during the cold period, and by using the groundwater, after a proper heat exchange, in order to run the capillary radiant tubes.

Several simulation boundary conditions concerning the above-reported occupancy patterns and building uses have been defined in a new numerical model of EnergyPlus. For examples, for what concerns the artificial lighting integration, in order to calibrate the model, we have lowered the illuminance levels in rooms, by defining time-averaged values (along the use of the building), in office rooms and services, equal to 350 lx and 150 lx, respectively.

In order to verify a suitable calibration of the model, statistical indexes, proposed by the M&V Guidelines "Measurement and Verification for Federal Energy Projects" [46] of the U.S. Department of Energy were calculated. This protocol proposes four options, from A to D, of available data and required aims, that can be grouped in "Retrofit Isolation" (i.e. Options A and B) or "Whole-Facility" (i.e. Options C and D) approaches.

The retrofit isolation approach (Options A and B) merely concerns particular systems or equipment, whose performance is not affected by the entire facility. With regard to the "Whole Facility method", Option C may be used for the data analysis of the entire utility. Based on the comparison between monitored and simulated data, Option D, "*can be used as either, but is usually applied as a whole-facility method*".

In our study, Option D, suitable for comparing measurements of energy meters and output of numerical simulations, was used. In order to deeply understand the reliability of our investigation, the indexes were not merely calculated for the whole facility, but for every system (heating, cooling, ventilation, auxiliaries, lighting) and according to the overall energy demand.

The following indexes, in particular, were calculated: mean bias error (MBE) and the coefficient of variation of the root mean square error (CV(RMSE):

- MBE: it allows to understand how well the simulation may predict the specific energy demand for a specific energy use by comparing the simulated value to the measured one. Positive values of the mean bias error testify an over-prediction of the numerical model. Conversely, negative values reveal an under-prediction. According to [46, 47], if a monthly analysis is under investigation, a calibrated simulation should be characterized by a monthly MBE value of less than 5%.
- CV(RMSE): the coefficient of variation of the root-mean-square error is a measurement of how uncertain the prediction is, and this refers to the whole energy use of a building. Due to the calculation method, the CV(RMSE) value is always positive.

As affirmed in a previous version of the M&V Guidelines of the U.S. Department of Energy [45], a building model "*is considered to be calibrated if its predictions of whole-building energy usage and its predictions of individual ECM energy usage are in agreement with measured data*". The building data have to include measures of energy demands, peak power as well as quantities of fuels. The data required are mainly the utility bill records (a minimum collection of 12 consecutive months, better 24 or 36 months [46]). With regard to the simulation, an hourly time step should be used, even if shorter intervals are recommended (15 minutes). According to this last requirement, all energy simulations carried out in the presented study were performed setting four time steps/hour (see Table II).

According to [45, 46], in order to calibrate an energy model, two macro-typologies of information are required. One is concerning the building and the other refers to active energy systems. Information on building these should be gathered both by documents and in-situ survey, and should concern building geometry and location (i.e. geometry, shape, orientation, shading elements) and the thermal physical properties of the building envelope (materials, constructions, thermal conductivities of layers, U_{VALUES} of external and internal envelopes, thermal mass, thermal capacity, etc.). Regarding active energy systems, the data for a suitable building modelling should include information, in order to correctly define the numerical model:

- primary systems of HVAC plants (e.g. chillers and boilers), about the installed power and capacity, numbers, operational schedules, etc.;
- secondary equipment of HVAC plants (e.g. terminal, air handling units, ventilation systems), also regarding motors, fan characteristics and head, flow rates at design conditions, operation;
- controls of the HVAC system (e.g. thermostat set points, control systems, deadband, tolerances);
- electric absorptions of plugged devices as well as information about the artificial lighting including numbers and types of lamps and operational criteria.

For the aforementioned version of the M&V Guidelines [45], the modelling and calibration of the energy performance of buildings are "*time-intensive activities and should be performed by an accomplished building simulation specialist. Calibrated simulation analysis is an expensive M&V procedure, and should be undertaken only on projects that generate enough savings to justify its use*". The document explicitly says that whole building simulation programs, being capable to perform simulations based on hourly weather data, have to be used. These softwares include EnergyPlus [46]. In general, the programs are acceptable if public, commercially available, suitable for defining the real building and its energy performance properly.

When the building model has been defined, a set of indicators, defined in the following Equations 7 to 10, can be used for analyzing the agreement between data measured (by energy billings or local metering devices) and simulation results.

The first step consists in calculating the mean bias error (MBE) evaluated in percentage terms according to both monthly and yearly periods. The MBE is determined by means of the following Equation 7, where "M" is the measured energy consumption in kWh and "S" is the analogous parameter evaluated by simulation. This indicator shows "*how well the energy consumption is predicted by the model as compared to the measured data*".

$$MBE\left[\%\right]=\frac{\sum_{period}\left(M-S\right)_{month}}{\sum_{period}M_{month}}\times 100 \qquad \text{(eq. 7)}$$

The following step (Equation 8) is the evaluation of the root-mean-squared monthly error (RMSE).

$$RMSE = \sqrt{\frac{\sum_{month} \left(M - S\right)_{month}^{2}}{N_{month}}} \qquad \text{(eq. 8)}$$

Moreover, Equation 9 (calculation of the average value of the monitored energy consumption: “A”) and Equation 10 (calculation of the coefficient of variation of the root-mean-squared error CV(RMSE) allow to understand the reliability of the simulation.

$$A_{month} = \frac{\sum_{year} M_{month}}{N_{month}} \qquad \text{(eq. 9)}$$

$$CV(RMSE_{month})[\%] = \frac{RMSE_{month}}{A_{month}} \times 100 \qquad \text{(eq. 10)}$$

When the month is the reference calculation period over the whole time horizon investigated, the following values are acceptable MBE and CV(RMSE values according to the aforementioned M&V protocol 2015 [46] and the ASHRAE Guideline 14-2002 [47] :

- MBE_{month} (%) ≤ ± 5%,
- CV($RMSE_{month}$) (%) ≤ + 15%.

a) Energy demand of each system and energy use

MBE as well as CV(RMSE) have been used for different comparisons. Table IV proposes the values of the aforementioned indicators, while Figure 10, with reference to both simulation and monitored data, shows a comparison for each specific energy use.

Table IV here

Figure 10 here

The values of the MBE are very satisfactory evidencing a suitable calibration of the model. However, the calculated values for CV(RMSE) underline some criticalities regarding specific energy uses of buildings.

More in detail, the high energy demand measured for September 2013 produces a high percentage gap between monitoring and simulated energy demands for heating. Here, it is quite evident that something strange happened in the real building use. Indeed, the energy demand for heating and DHW of September 2013 has too much increased compared to the ones of August 2014.,Considering that September 2013 has been the first month of the building operation, something with the space heating management apparently did not work properly..

The same happens in April 2014, characterized by a measured energy demand for heating lower than the one of May. Moreover, something wrong also happens in November and December 2013, even if it seems that the mismatching is due to some particularities in the operation of the HVAC system, the demand of December being lower than the one of November (of course, the simulation gives an opposite result). Even if the Christmas holidays are taken into consideration, this is not enough for explaining the lack of agreement.

With reference to all other energy uses and thus the energy demand for ventilation, lighting, pumps, equipment, the agreements between simulation and measured data are quite satisfactory. Of course, also in this case, some punctual and normal gaps could be found (for instance regarding the energy demand for lighting in April 2014).

In general, the highest gaps were registered in September and October 2013 (e.g. see the energy demands for equipment) and thus when the building is in the first months of operation, so that there is not a "steady-state" use of it. It means that the building is not fully occupied and also the management of the various energy active systems was characterized by a normal, initial lack of expertise.

It is noteworthy to underline that, even if particular phenomena provide a CV(RMSE) higher than the ones admitted in some cases, however, the MBE is always significantly lower for every energy use compared to the admitted threshold. In particular, the indexes of calibration are the following ones (Question 5 R2):

- space heating and domestic hot water: MBE_{month} = -1.16%, CV(RMSE) = 32.50%
- pumps and Fans: MBE_{month} = 0.88%, CV(RMSE) = 12.58%
- lighting: MBE_{month} = -0.67%, CV(RMSE) = 17.46%
- office Equipment: MBE_{month} = 1.95%, CV(RMSE) = 21.91%
- all electric uses: MBE_{month} = 1.15%, CV(RMSE) = 7.96%

The satisfactory calibration of the energy model is quite evident. In detail, the mean bias errors range between -1.16% and 1.95%, while the admitted limit is ± 5%. Moreover, in order to be as accurate as possible, in this paper the comparisons have been carried out for every energy use, while the M&V document [46], Option D, underlines that the evaluation can be done with whole-building or end-use metered data or both. In this case, and thus if the overall energy demand of building is considered, the results of Figures 11a and 11b are calculated. Here, the annual MBE is +1.15 and the CV(RMSE) is 7.96%. As is clear, the calibration is completely satisfactory, even if the criticalities of the first period are taken into account.

Figure 11 here

All in all, it is important to underline that, independently from the accuracy of a building-related numerical model, some events, such as a particular building management, an anomalous use of the building and/or a particular behavior of the occupants, are unpredictable phenomena.

b) Energy need for space cooling

As discussed in Section 3, the building requires thermal energy for cooling purposes, also during the intermediate seasons and in wintertime. This is quite common in high-insulated buildings, also in heating-dominated climates. Regarding UBA 2019, following a suitable heat exchange with a secondary fluid, the direct use of groundwater allows a passive cooling of the building, if and when required along the whole year. Finally, no chillers are needed to cover the cooling demand. The cold water is used both for the cooling coil of the ventilation system, in the air handling unit placed at the ground floor and for the capillary radiant system (embedded in the partition walls of each office). Every single room is equipped with a condensation sensor to avoid the phase change of vapor on the cold surface of the wall. Finally, with the exception of the electric energy required for the pumping, the building is passively cooled.

However, during the cooling operation, a variable set point can be chosen, ranging from 22 °C to 26 °C, depending on the season. Also in this case, the occupant can manage the set point of the room by increasing or reducing the desired comfort temperature. The chosen general criterion is an indoor set point, during the warmest period, 6 K below the outdoor air temperature. In any case, regulation systems are installed in each single office.

It is clear that the prediction of energy demand for cooling is quite complicated, because this is strongly related to: a) the design of the building (high insulation and thus cooling demand along the whole year), b) the occupants' behavior (managing of the indoor set point in each room), c) the efficiency of the heat exchanger. Moreover, this was the first year of the building operation, so that the use of the UBA 2019, as previously said, also showed the typical criticalities linked to the start-up of a new high-tech edifice. In particular, both systems and knowledge of these require training, mainly in the first months.

In Figure 12, a comparison between the measured cooling need (this is the sum of the cooling provided by the ventilation system and by the radiant devices) and the ones calculated through the transient numerical simulation is presented, in terms of thermal energy. It is evident that some performance gaps occur.

Figure 12 here

It is also evident that the trends of measured cooling demand are affected by criticalities, while the simulation results are similar to the expected ones. In particular, by comparing the demands not affected by peculiarities, a good agreement can be found in each season (autumn, winter, spring, summer - see, for instance, October 2013, January 2014, April 2014, August 2014). Nevertheless, some months show large gaps:

- November has a cooling demand much lower compared to October and December,
- July shows a cooling request much higher than June and August.

Mainly this last event is not completely reliable, even if, as shown in the following lines, the third week of July 2014 was very warm (the monitored indoor temperatures were the highest of the month also in another naturally ventilated building in Berlin, [76]). On an annual basis, the MBE is 9.84%, due to a simulated cooling demand of 19'740 kWh_{TH} (16.7 kWh_{TH}/m^2a) and to a measured one of 21'896 kWh_{TH} (15.6 kWh_{TH}/m^2a). Finally, also in this case, a calibrated building model may identify the general trend. It is noteworthy to underline that the cooling demand is greatly affected by solar radiation, more than by the outdoor temperature. Finally, the result of calibration, according to the authors, is also acceptable in this case.

c) On-site energy conversion from photovoltaics

According to the building design, the photovoltaic (PV) energy production, on an annual basis, should be 52'461 $kWh_{electric}$, as discussed in Section 4.1. That would allow a complete net zero energy building (here the reason is the UBA 2019, because the requirements of the 2010/31/EU Directive would already be largely satisfied, also with a slight surplus of energy from renewables compared to the demand). Really, after one year of monitoring, the measured electric conversion has been much higher, i.e. 69'167 $kWh_{ELECTRIC}$. The annual gap between monitoring and design has been +32%. The mismatching between design and measurement is due to the higher efficiency of the installed system compared to the designed one, the size of the photovoltaic field as well as the installation boundary conditions being exactly the same. Finally, the 66.3 kWp system, compared to the presumed conversion of 790 $kWh_{ELECTRIC}$ /kWp, has a much higher production, being 1'043 $kWh_{ELECTRIC}$ /kWp. In this case as well, the numerical model has been newly calibrated. More in detail, by varying the efficiency of modules and equipment in EnergyPlus, the results of Figure 13 have been calculated.

Figure 13 here

A very favorable matching between measured data and ones predicted by means of EnergyPlus can be seen. In particular, the same indicators previously presented, and thus MBE and CV(RMSE) are always favorable. Annually, the MBE is -0.22%, while the CV(RMSE) is 15.5%, and thus both are lower than/correspond to the limits suggested by the ASHRAE (MBE_{month} (%) ≤ ±5%, CV($RMSE_{month}$) (%) ≤ +15%). If the value of September 2013 is not considered (it is important to remember that this is the start-up month, characterized by a generalized mismatching between simulation results and measurements, with reference to almost all energy uses), the CV(RMSE) would be 11.7%, much lower than the limit of 15%.

Definitively, the building model can be considered to stand for the present scenario being calibrated towards the present energy performances. Finally, the related trends of Table IV and Figures 10, 11, 12 and 13, revealed a quite good agreement between measurements and simulated results, and thus the numerical model can be considered reliable in predicting the building performances, in terms of energy demand and energy production, according to the actual conditions of use and behavior of occupants.

The M&V Guideline in Table 4.1 affirms that "*After the model has been calibrated, savings are determined by comparing a simulation of the baseline with either a simulation of the performance period or actual utility data*". This will be done in a next study.

d) Indoor microclimate

Once a high reliability of the model in predicting the building behavior in terms of energy needs, electricity demand and electric conversion from renewables is evaluated, a check concerning the trends of indoor temperatures is necessary. Indeed, the reliability of an energy model has to be verified in terms of both electric meters and consistency of trends of measured and simulated indoor conditions. It should be noted that, even if the building was used from September 2013, a first period of some months was necessary to fine-tune the monitoring system completely, so that systematized and completely reliable measurements of indoor conditions were available starting from spring 2014.

In Figures 14 and 15, for two weeks of the summer 2014 and winter 2015 respectively, trends of outdoor temperatures (graphs A), indoor temperatures (graphs B, C, D) are reported by comparing measurements and the outcomes of simulations. Both Figures merely concern the fully occupied hours, and thus the time between 8 o'clock in the morning and 6 o'clock in the evening, starting from the 7th day of the month and for the next 14 days. Regarding July 2014, the IWEC weather file well represents the measured outdoor temperature for the first week, while, starting from 14 July, the outdoor measured temperatures also were more than 10 °C higher than the ones of the hourly weather file. In the period 07/07/2014 – 13/07/2014, in particular, the mean gap between measurements and predictions was 0.07 °C, while the same value, for the period 14/07/2014 – 22/07/2014, was about 11.3 °C, with the real outdoor conditions being very warm. This underlines a worrying phenomenon of generalized warming of climate. Indeed, the entire year 2014 in Berlin was significantly warmer than the average. Concerning the indoor temperatures, the following monthly average gaps have been registered between measurements and simulations:

- ground floor, office 1, east exposure: -1.43 °C (MBE_{month} = -5.98%),
- first floor, office 3, west exposure: -1.06 °C (MBE_{month} = -4.45%),
- first floor, office 3, north exposure: +0.27 °C (MBE_{month} = +1.06%).

Figure 14 here

The aforementioned value, once again, evidences how the difference in the external conditions also affects the indoor air temperature. Indeed, in the case of high solar radiation, the occupants tend to cool more the indoor air, given the comfort conditions related to the operative temperature, in order to have comfortable environments. Regarding the office exposed to north, however, the effect of solar radiation is obviously very low due to the exposure and also given the porch behind the building, so that the correspondence among measurements and simulations is much better.

Regarding the winter season, the first reliable monitored data are those of the following year, so that comparison among simulations and measurements, concerning the calibration of the building model (developed in summer 2014), is merely qualitative.

In Figure 15, graphs B, C and D, it can be seen that the trends of indoor air temperature are very similar for the offices exposed to the north and east sides and the upper floor compared to the ones on the ground floor, i.e. on the east side. In detail, the following monthly-averaged gaps have been calculated:

- ground floor, office 1, east exposure: -1.14 °C (MBE_{month} = 5.06%),
- first floor, office 3, west exposure: -0.05 °C (MBE_{month} = -0.23%),
- first floor, office 3, north exposure: -0.17 °C (MBE_{month} = -0.80%).

Figure 15 here

All told, for what concerns the indoor air temperatures, the same threshold of calibration, and thus $MBE_{month} \leq \pm 5\%$ (established by the authoritative Ref. [46, 47], even if concerning the energy demands) has been taken into consideration. Only one room at the ground floor has a slightly higher MBE.

6. Further remarks and perspectives

UBA 2019 was designed as one of the first German net zero energy buildings of the public sector, being used by the German Federal Environment Agency. According to the building design, the expected energy performances, in terms of electric energy demand and in-situ production by electric renewables, should be the ones shown in Figure 16a, which shows a light annual overproduction of electricity by installed photovoltaic system compared to the energy demand of the building. By taking the concept of Figure 1 into account, the aim should be to have a net zero energy building on an annual basis with an electricity conversion almost 15% higher than the energy consumption.

Figure 16 here

After one year of monitoring (measurements in Figure 16b), the overall energy demand is very similar to the expected one, even if this is the sum of several energy uses. By analyzing the specific energy use, substantial differences exist among design expectations and measured data. For instance, as discussed in the Section 4, the real energy demand for heating is much higher than the expected one, while the energy required for the domestic hot water is very low. Other important gaps between design and measurement concern the energy demands for auxiliaries, ventilation, artificial lighting and office equipment. With the exception of the energy demands for heating, all measured energy demands, for every use, are lower compared to the ones predicted during the design phase.

Globally, by considering the overall electricity consumption, the measured value is similar to the expected one (design condition), even if, as said, it is derived from contrasting phenomena with reference to the peculiar energy use. All in all, the building requires around 44’000 $kWh_{ELECTRIC}/a$. Considering an average thermoelectric efficiency of the German electric facility [68] and a heated area of the building of 1’178 m^2a, this means a primary energy demand, for all energy uses, of 96 $kWh_{PRIMARY}/(m^2a)$ (i.e. 37 $kWh_{ELECTRIC}/(m^2a)$). This is a very satisfactory outcome, even if the repartition, among energy uses, has been quite different compared to the expected one.

However, the expected energy conversion by means of photovoltaic is largely lower than the measured value. According to Figure 16b, the measured energy demand is 43’827 $kWh_{ELECTRIC}$, while the in-situ conversion is around 69’167 $kWh_{ELECTRIC}$, so that the target of net zero energy building is perfectly achieved, at now and in the future, by taking a typical decay of building/system performances into account.

Presently, however, the building is grid-connected, so that the electricity produced by the photovoltaic system, when not required by the building itself, can be supplied to the grid on the site where the building is located or to the public grid. Nevertheless, in hours characterized by an electric demand higher than the production from photovoltaics, the building draws electricity from the public grid.

With regard to the present German net-metering and feed-in-tariff systems, maximizing the self-use of the converted energy is convenient, so that, in order to make the whole present UBA 2019 system really convenient, an optimization study is necessary. It is presently being developed and aimed at improving the self-use of electricity from in-situ renewables by means of suitable storage systems. More in detail, the authors of the present paper - according to common criteria for proper feasibility studies - now investigate typology, size (power, kW), electric storage (kWh) and electric charge (Ah) of a new storage system, not yet installed. Beyond the economic profitability, indeed, the self-use of electricity produced on-site is also necessary in order to design “real” net zero energy buildings. If we think to the future, when the share of net zero energy buildings will be significant, a great disequilibrium between the seasons (energy bought by the grid in winter, energy supplied into the grid in summer) could be problematic also at urban level. Finally, in the design of buildings, also the concomitance between in-situ conversion and use of energy must be taken into account (also by considering diversified renewables, such as micro wind technologies, beyond the photovoltaic system). Today, UBA 2019 only uses 27% of the electric energy converted by the on-site photovoltaic system. The most part of its electric demand is covered by buying electricity from the public supplier. The size of the PV system, not optimized with respect to the electricity demand, highlights a general issue that concerns the construction of all NZEB. The main problem is that consumption for air conditioning is reduced in the summer season, in the case of NZEB, while the electric conversion from photovoltaics grows significantly. It is therefore necessary to design an Electrical Energy Storage (EES). Starting from the present measured electric demand, by means of TRNSYS [67], a EES system has been modelled by simulating different capacities and powers for storage. A technical and economical study has been performed by taking all costs (value of supplied energy, the value of bought energy, investment and maintenance of the batteries) into account in order to optimize both the self-use (maximization) and the cost of stored kWh of electric energy. The capacity of batteries that maximizes the self-use (≈ 42%) is 10 kWh, with a peak power of 39 kW, but it induces a cost of the system of 0.27 €/kWh comparable to the price of supply by the public grid. Therefore, in order to optimize the size, a cumulative frequency of the required power on an hourly basis in the charging and discharging phases has been built. With a capacity of 10 kWh and a peak power of 16 kW, the cost of stored kWh goes down to 0.21 €/kWh by increasing the self-use until 38%. This is not the maximization but the technically most economical solution. Finally, having achieved a calibrated model, the same study will also be performed for different scenarios, once modifications have been applied to the building envelope, the HVAC system, the installed renewable energy sources. Finally, the main motivation for having a calibrated model of the building is the future evaluation of possible energy efficiency measures, in order to have the possibility to perform trustworthy feasibility studies on the basis of a reliable present scenario.

Conclusions

The building sector is responsible for the highest energy demand and related pollutions worldwide and at EU level, so that, recently, the EU members shared new guidelines in terms of refurbishing the existing stock as well as the design of new nearly zero energy buildings. In this context, the buildings of the Federal Government in Germany are presently more efficiently designed compared to the law requirements. This study proposes a large investigation of a new public building in Berlin by design, measurements and calibrated, hourly energy simulations, considered to be eco-sustainable and compensating the energy demand by a local conversion of energy from on-site renewable energy sources: geothermal, thermal solar and photovoltaic energy.

During the first year of operation, performance gaps occurred among measured energy performances and expected ones. Indeed, even if the overall electric energy demand is similar to the expected, the single energy uses for specific needs (i.e. heating, lighting, ventilation, auxiliaries, equipment) are quite different compared to the design. The reasons for that are related to the pattern of use of buildings and to the occupants' behaviors. Finally, as common in energy projects, significant performance gaps were found, mainly due to natural ventilation rate and managed indoor set points. In particular, the manuscript shows that, even if the total electric energy demand, designed and monitored, is very close to the designed, the share of incidence of the single energy usage is quite different. In detail, there is a much higher energy demand for heating (i.e. 2.7 times the expected request), including DHW production, which has a very low impact, while the measured demands for ventilation, lighting, equipment are much lower, about -36%, -33%, -14%. Conversely, the measured electricity production from photovoltaics is much higher than the designed, + 32% and thus the building is not classified as a „zero“ but a „plus“ energy house.

The present investigation was aimed to adopt transient energy simulations to understand the reason of this mismatching and to develop a numerical model, properly calibrated, suitable for testing scenarios of improvement. In order to test the quality of calibration, the mean bias error (MBE) and the coefficient of variation of the root mean square error CV(RMSE) were calculated for the specific energy use, for the cooling need and photovoltaic production. All indicators give satisfactory evidences of the quality of the numerical model, for what concerns the energy demand for heating and domestic hot water (MBE = 1.16%), energy for pumps and fans (0.88%), artificial lighting (0.67%), office equipment (1.95%), total electricity (1.15%) and on-site electric conversion from photovoltaics (-0.22%). At the same way, a comparison among indoor temperatures in June 2014 and January 2015 (two central weeks of the months) provides comparable trends of measurements and predictions.

Starting from a numerical scenario, capable to interpret the actual building behaviors, the next step will be to optimize the self-use of the energy converted “on-site”, in order to optimize the storage system for the electricity produced under both technical and economic points of view. Indeed, the present policies of net metering and feed-in-tariffs in Germany make the on-site use of the converted energy compared to the exchange from and to the grid much more profitable. This will be an interesting study looking to the future, in order to have a higher equilibrium between building energy production and building energy demand. First outcomes have already been proposed in this study.

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Figures' Caption

Figure 1 – Concept and strategies for achieving net zero-energy buildings: a) definition, b) relation between energy efficiency of envelope/active systems and need of on-site energy conversion

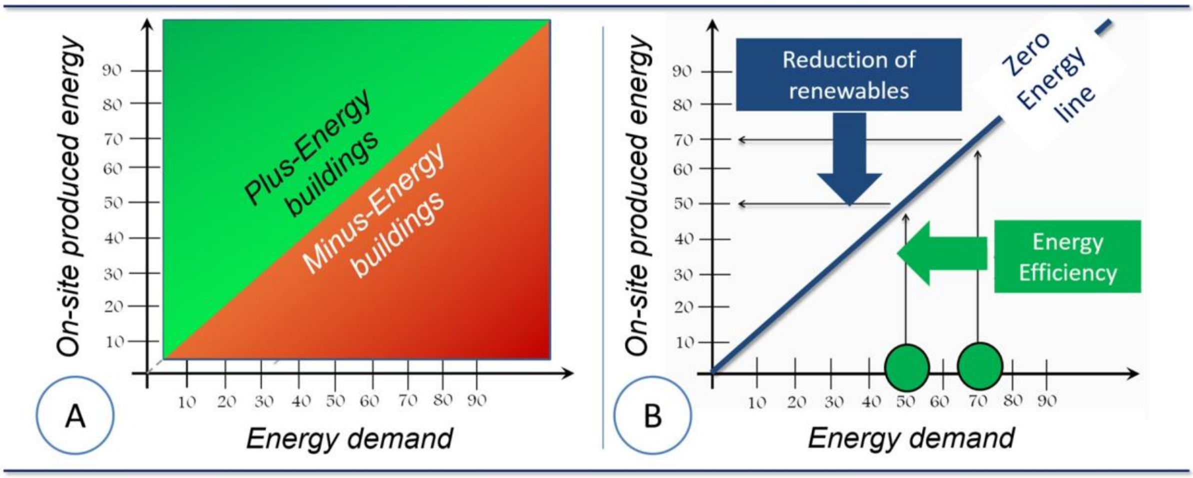

Figure 2 – the net zero-energy house UBA 2019 in Berlin Marienfelde: a) South Façade, b) Air Handling Unit, c) West Façade, d) under-floor primary air distribution system

Figure 3 – Indoor distribution of the building: a) Ground Floor, b) First Floor

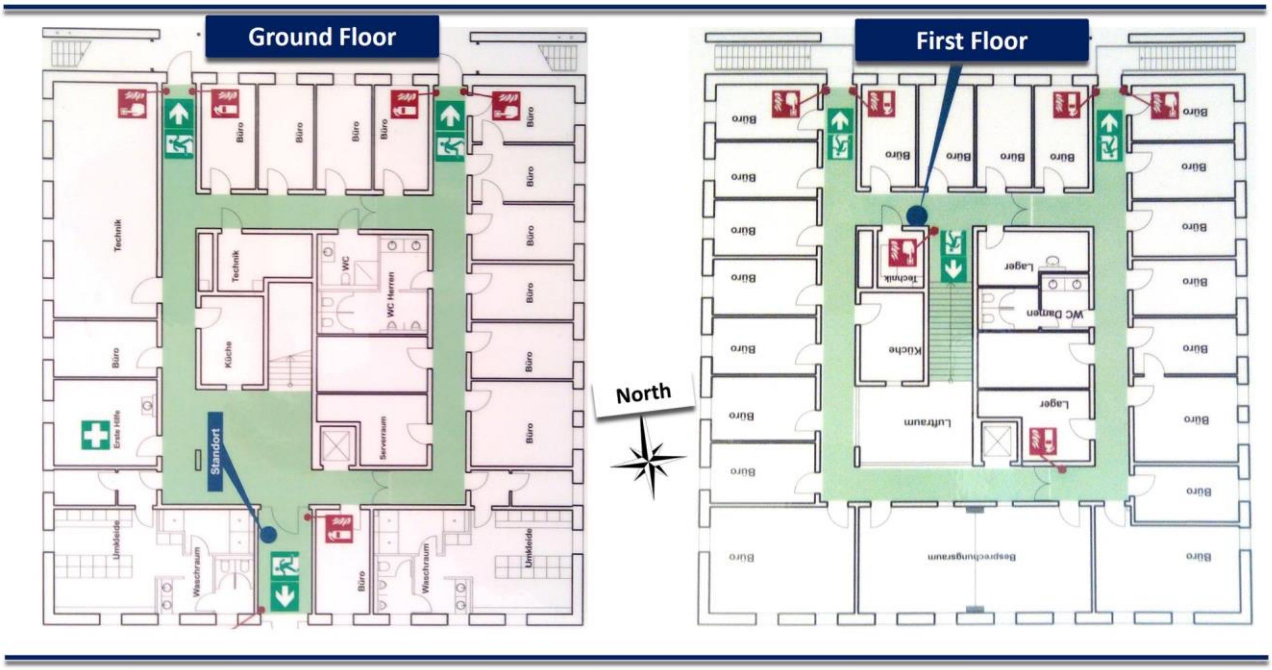

Figure 4 – Energy Concept of UBA 2019

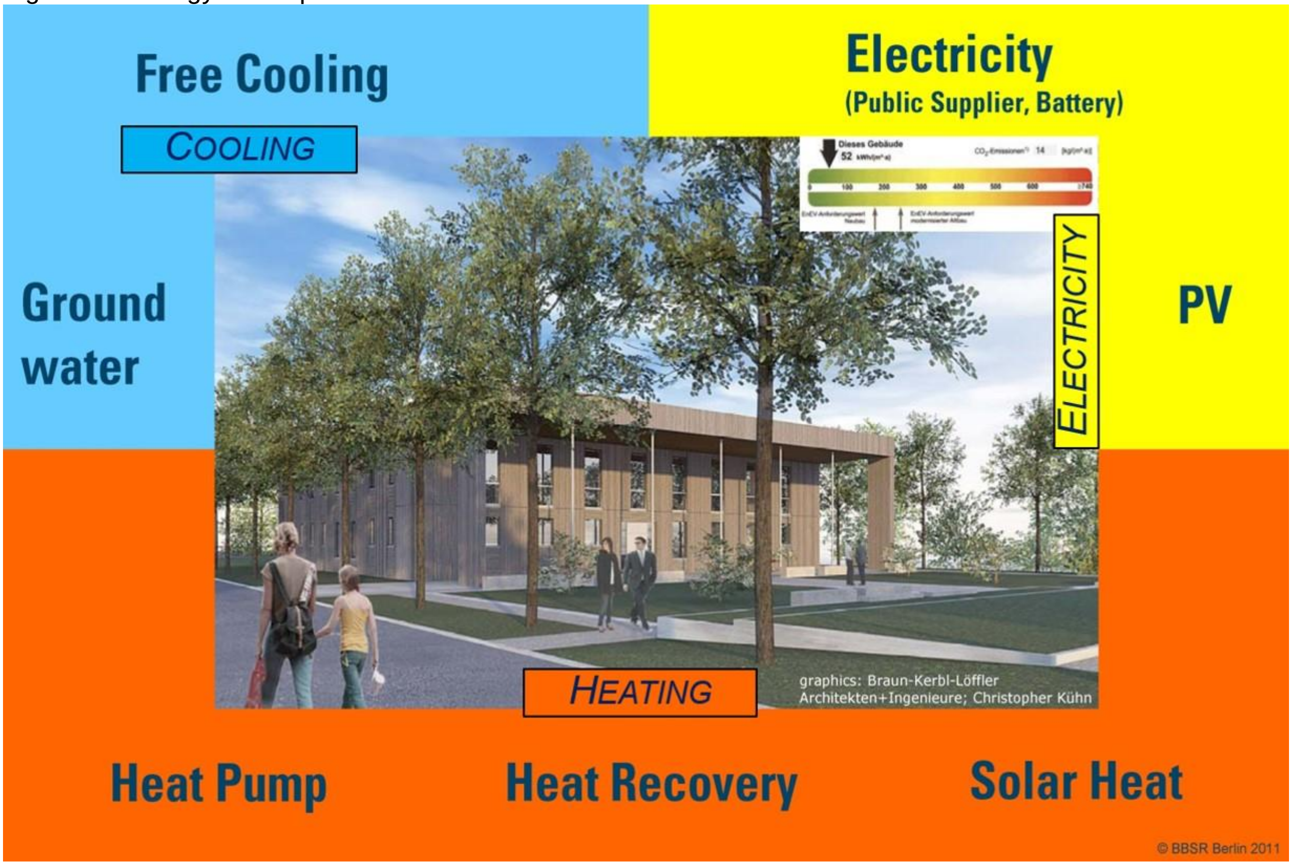

Figure 5 – Real and modeled building: geometry, shape and aspects

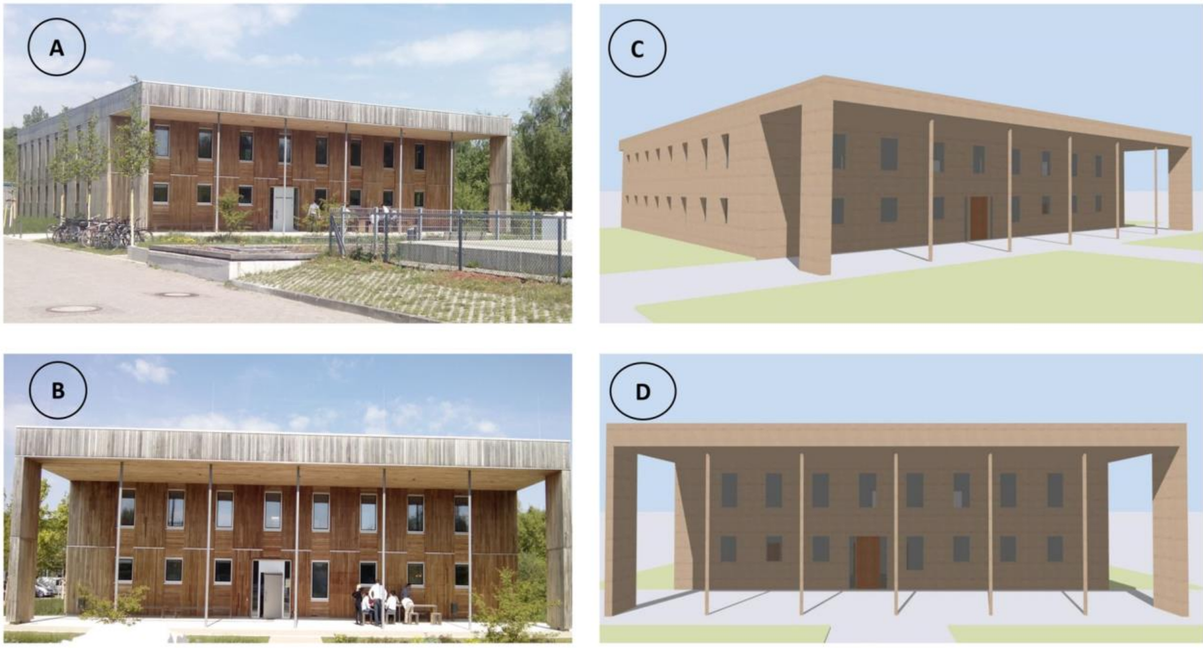

Figure 6 – Real and modeled Building: overview of solar and photovoltaic systems on the roof

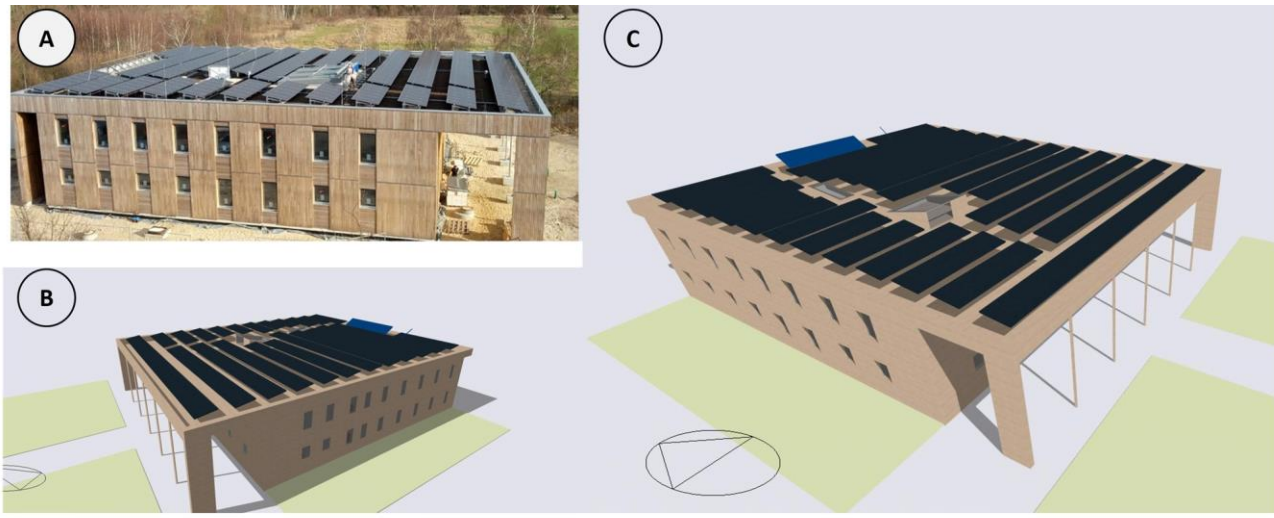

Figure 7 – UBA 2019, Electric energy conversion by PV system: comparisons of values calculated with EnergyPlus and PV-Gis

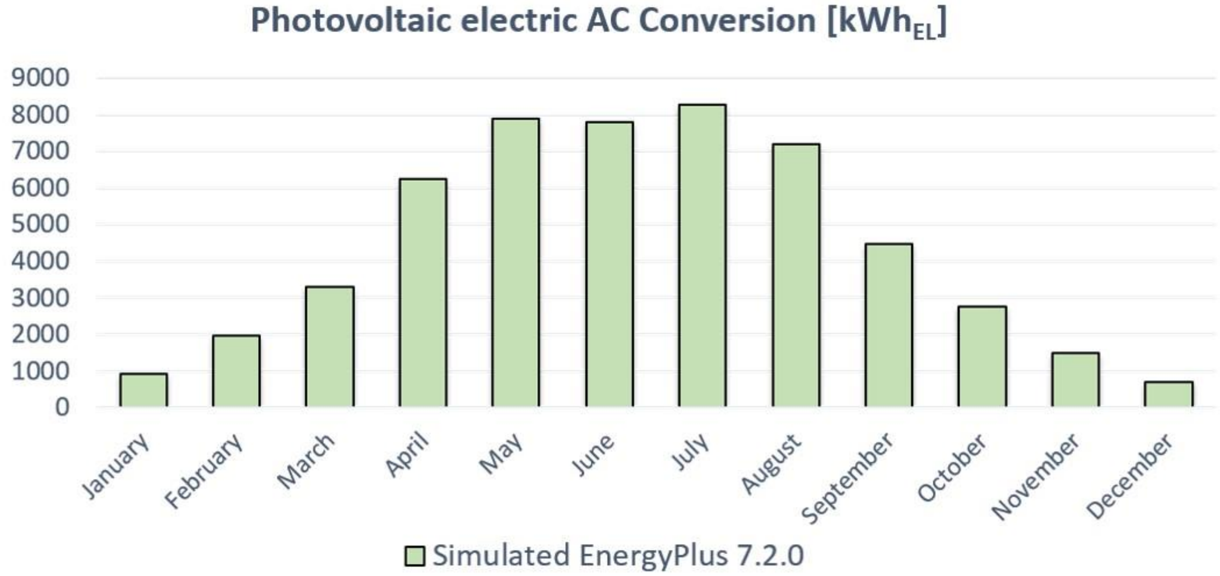

Figure 8 – Schematic diagram of energy systems and monitoring apparatus

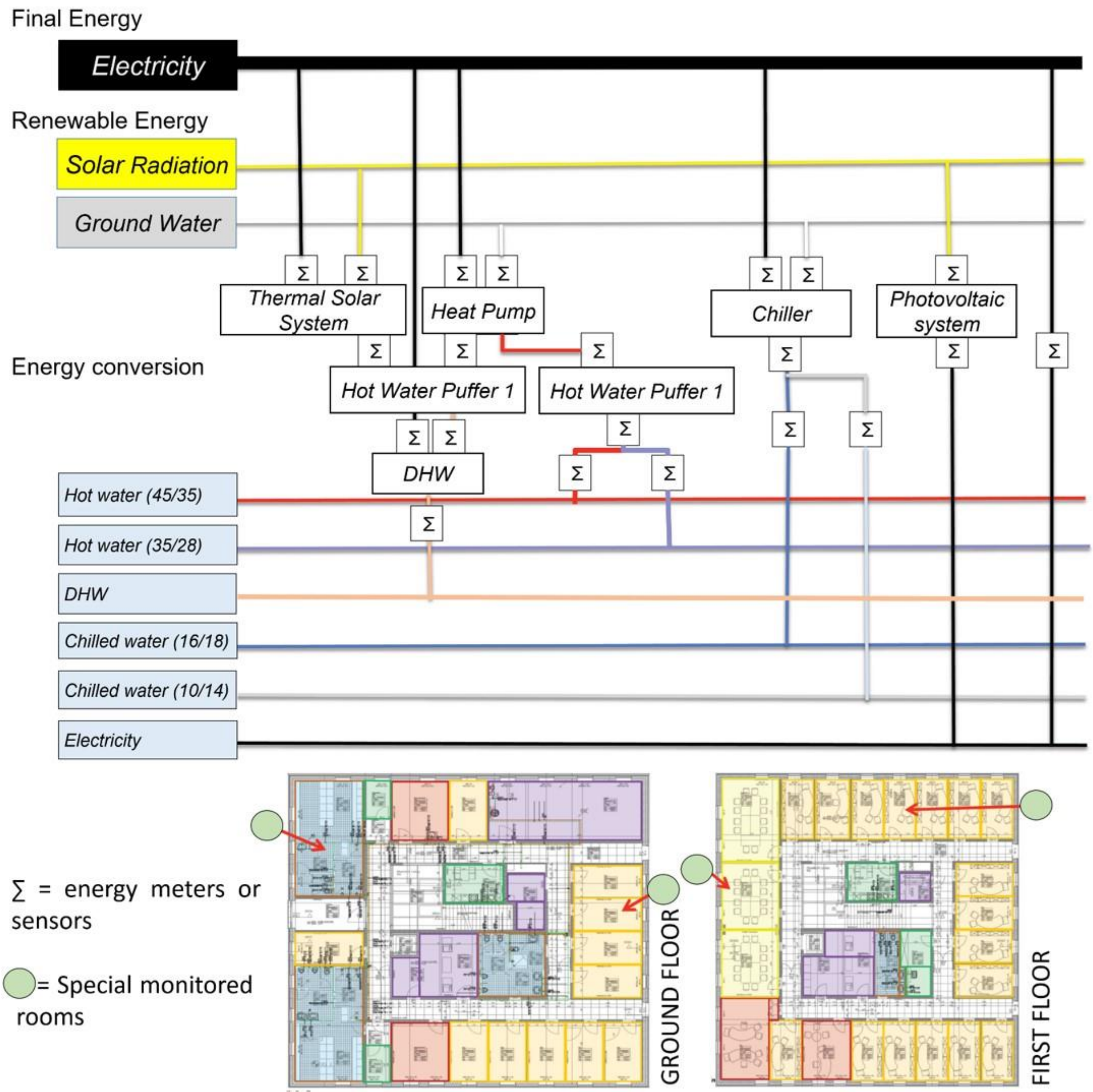

Figure 9 – Annual electric energy demand for specific uses: a) absolute values, b) percentage differences

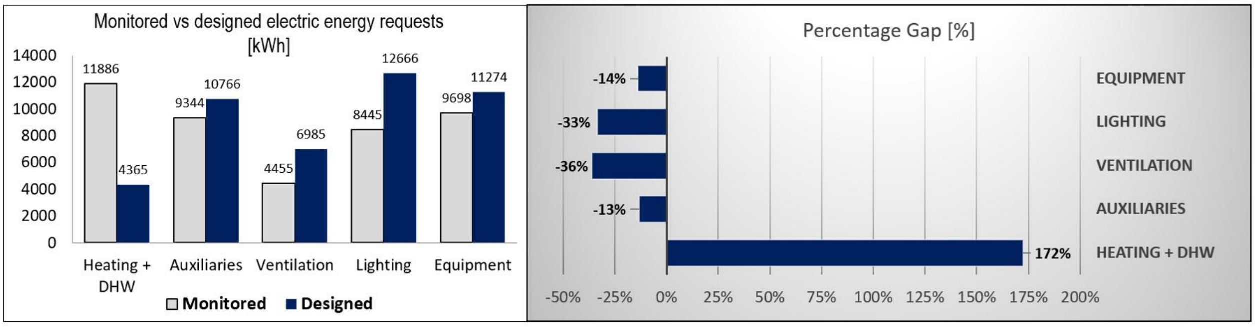

Figure 10 - Monthly comparisons of energy demands between monitored and simulated data, with reference to: a) electric energy for the space heating and DHW, b) auxiliaries and ventilation, c) lighting, d) office equipment

Figure 11 - Monthly comparisons of the overall energy demand, between monitored and simulated data (a) and monthly values of the Mean Bias Error and its trend (b)

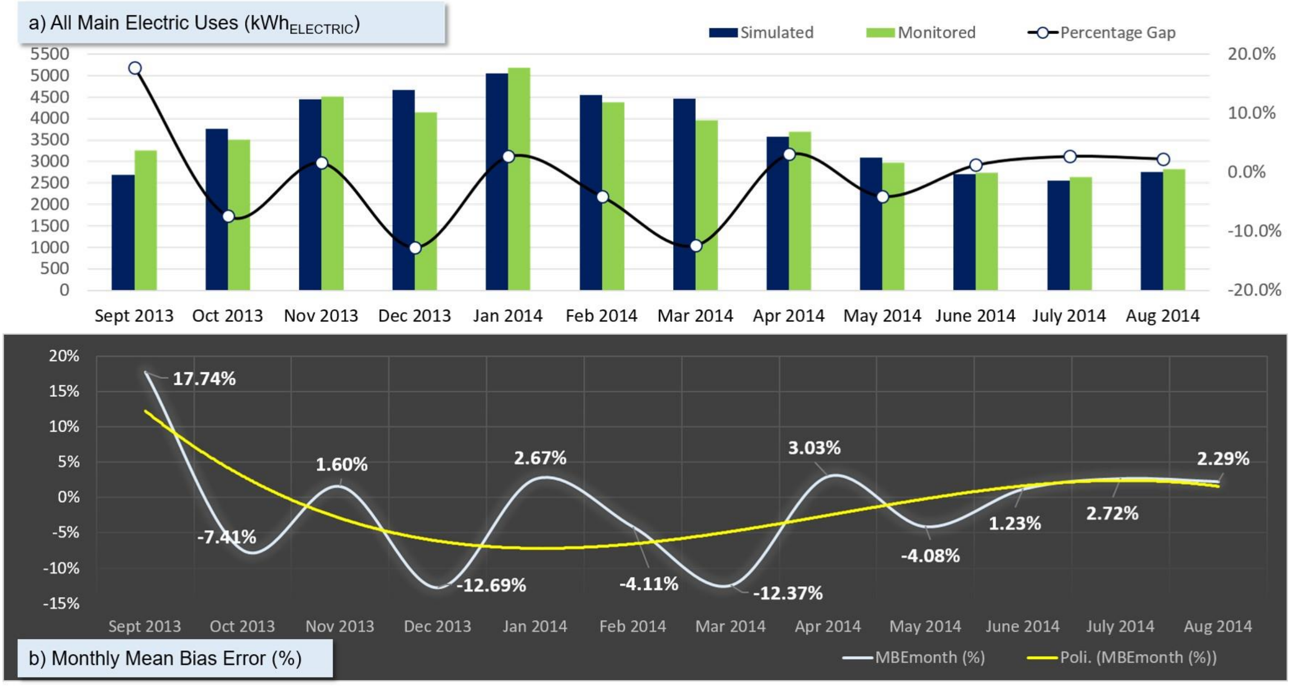

Figure 12 - Monthly comparison of the overall energy need for the space cooling (thermal energy)

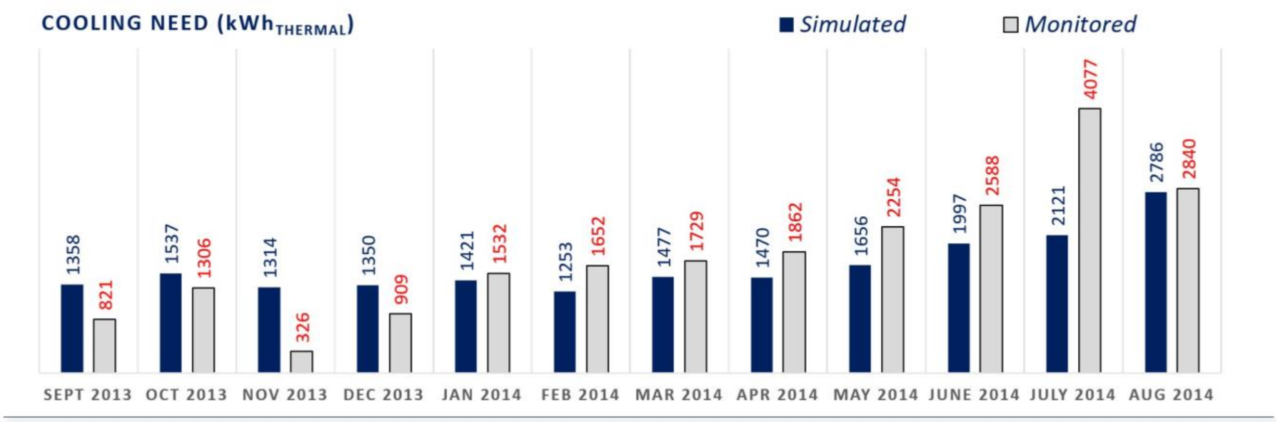

Figure 13 - Monthly comparisons of the energy converted from the photovoltaic system, between monitored and simulated data (a) and monthly values of the Mean Bias Error and its trend (b)

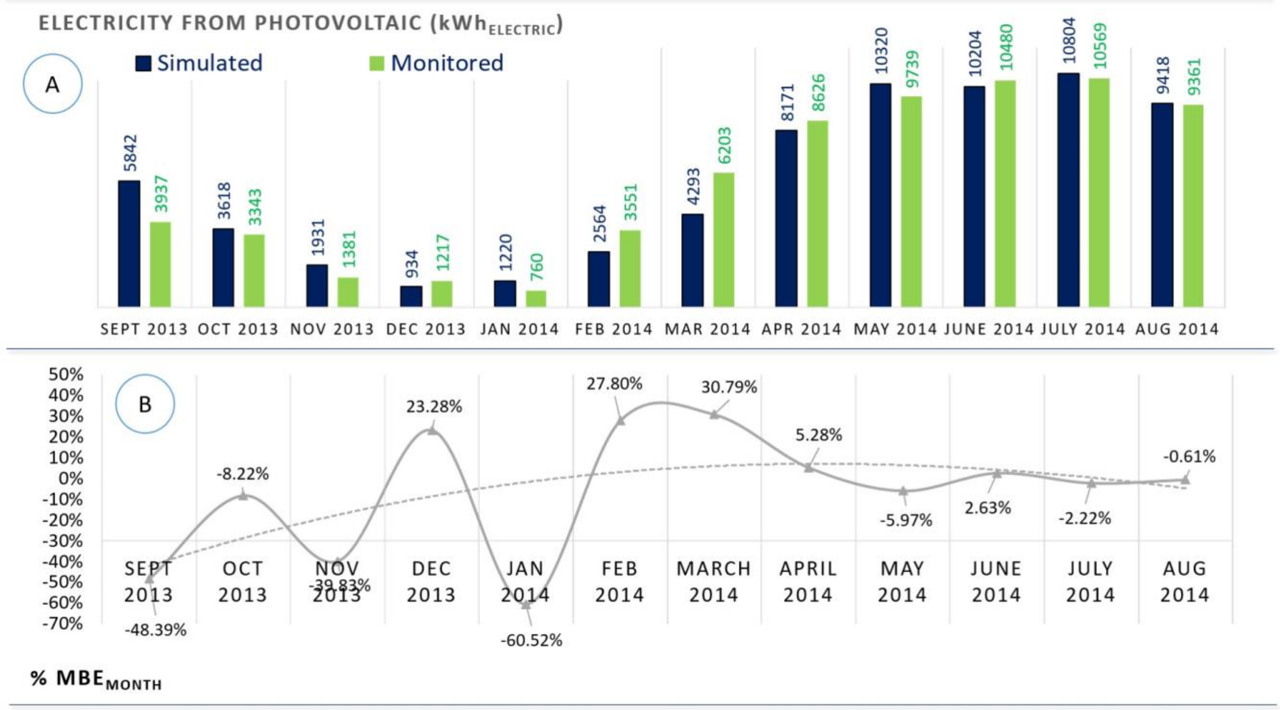

Figure 14 – Central Weeks of July 2014. Comparisons among measured and simulated outdoor temperatures (A) and indoor temperatures in selected offices (A, B, C).

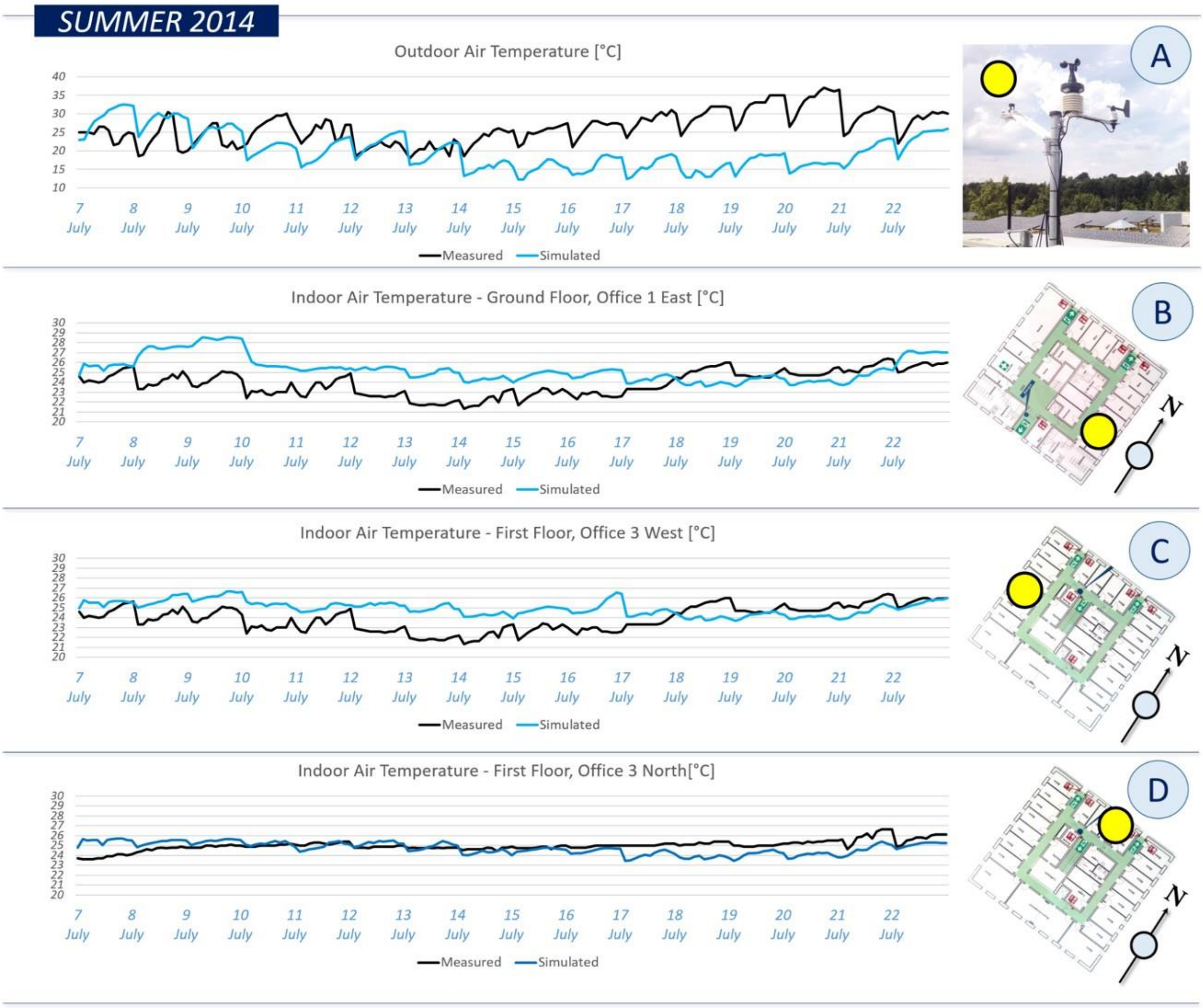

Figure 15 – Central Weeks of January 2015. Comparisons among measured and simulated outdoor temperatures (A) and indoor temperatures in selected offices (A, B, C).

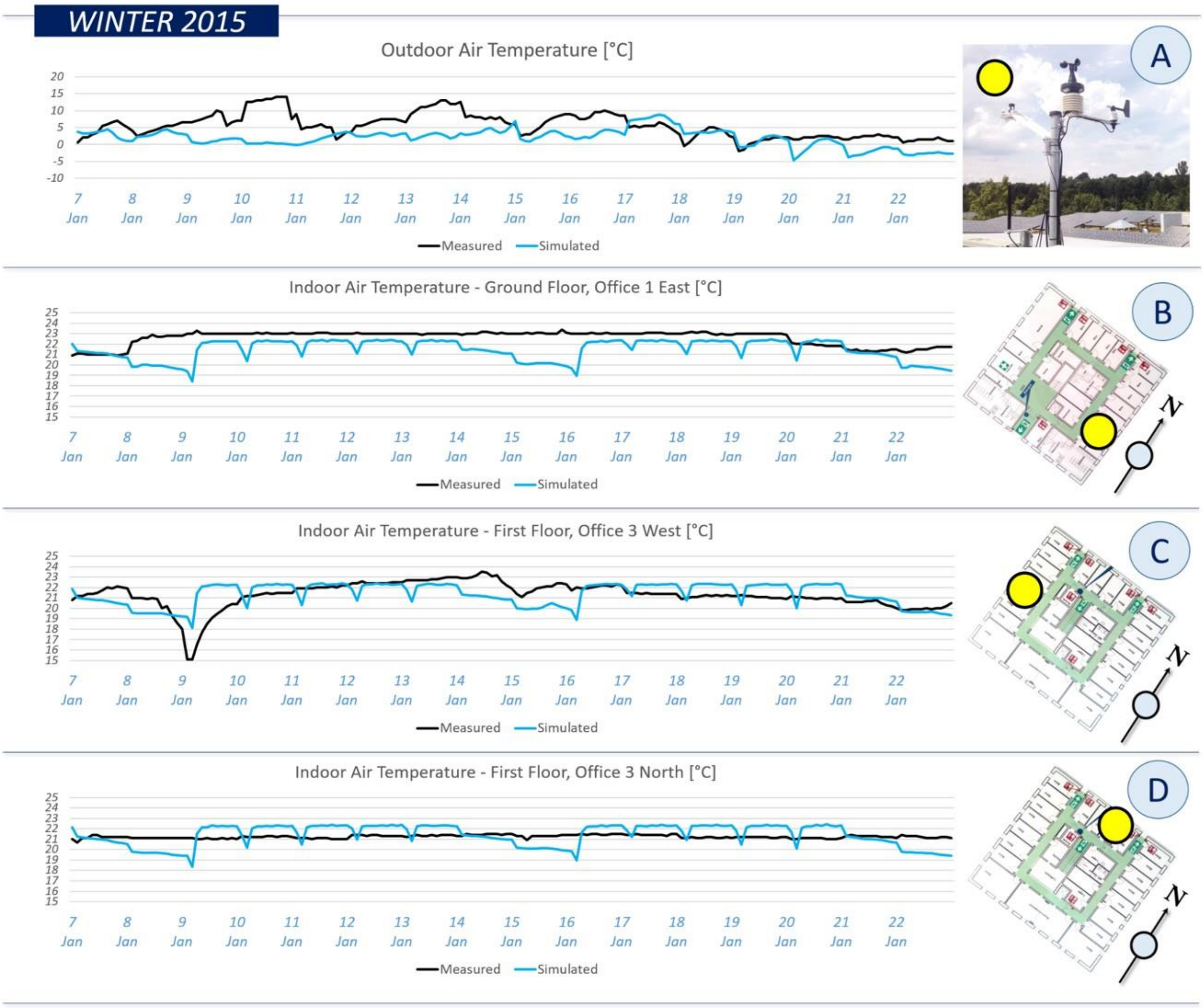

Figure 16 – a) Designed and b) Real buildings: energy requests and on-site conversions by renewables

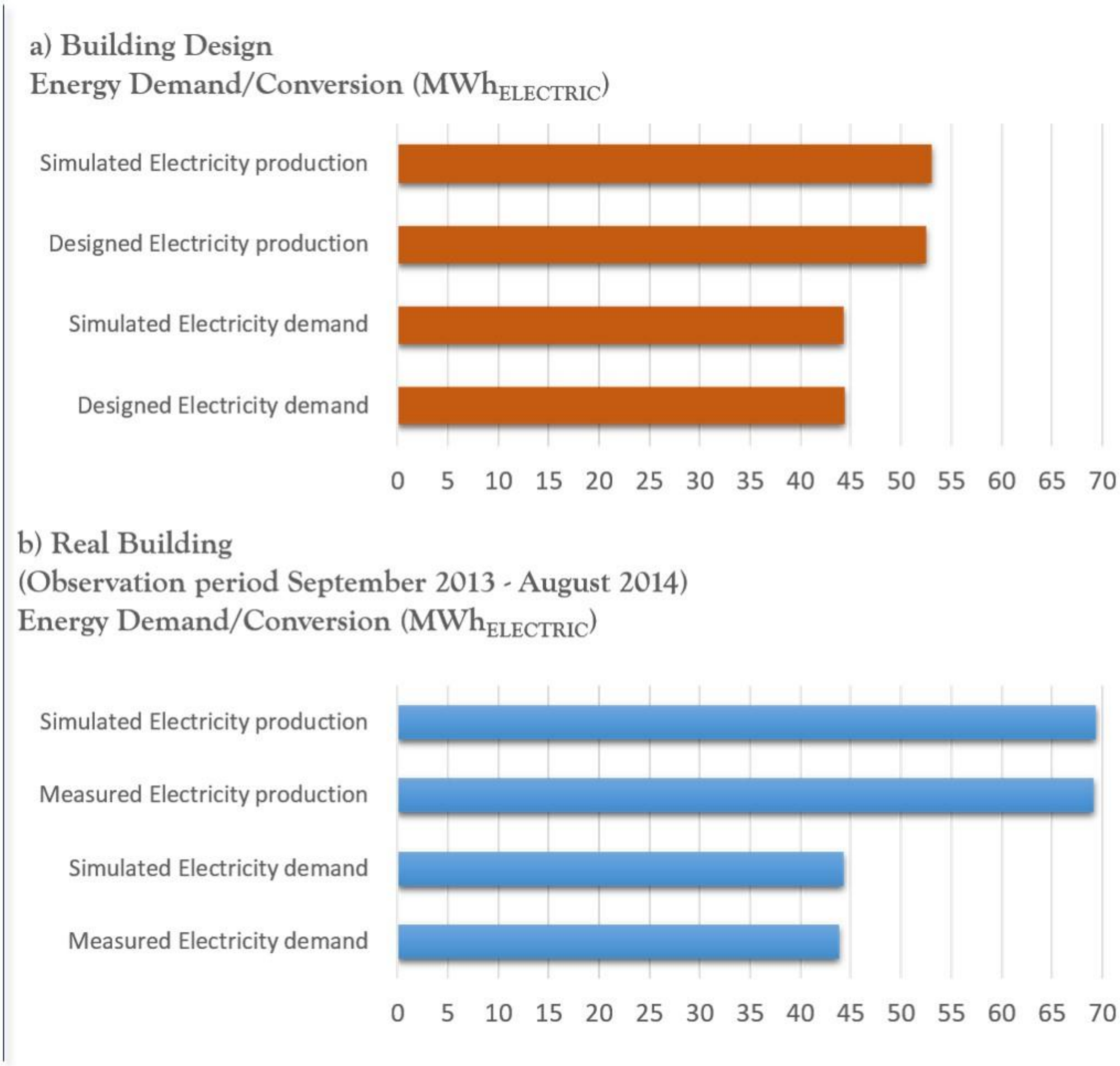

Table I – Building characteristics, HVAC systems descriptions, renewable systems, boundary conditions and energy related parameters

MAIN BUILDINGS DIMENSIONS			
Gross Length (N-S direction)	25.12 m	Gross Floor Area	1178 m^2
Gross Length (N-S direction)	25.12 m	Gross Volume	3862 m^3
Gross Length + Porch + Stairs	30.40 m	Roof Area	599 m^2
Gross Height	7.2 m (2 floors)	Surface to Volume Ratio	0.48 m^{-1}

BUILDING GEOMETERY					
	TOTAL	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m^2]	656.1	162.0	164.9	164.2	164.9
Window Area [m^2]	106.4	18.8	31.8	29.1	26.6
Window Wall Ratio [%]	16.2	11.5	19.3	17.8	16.1

INFORMATION ABOUT SITES, CLIMATES, INDOOR USES AND ENDOGENOUS GAINS			
Weather data	ASHRAE Berlin IWEC → EPW	Number of zones	58 Thermal zones
Set point during the heating time: Offices Common spaces Technical rooms	 22 °C (Off between 19.00 - 08.00) 22 °C (Off between 19.00 - 08.00) 15 °C (Off between 19.00 - 08.00)	The set point of temperature for cooling is variable according to the trend of ambient temperature, ranging from 22 °C during the cold season, to 26 °C during the full summer. In the hottest summer days, it is 6 K lower than the outdoor temperature.	

BUILDING ENVELOPE			
U_{WALL} (weighted average method)	0.12 W $m^{-2}K^{-1}$	$U_{WINDOWS}$	0.70 W $m^{-2}K^{-1}$
U_{ROOF} and $U_{FLOOR\ ON\ THE\ GROUND}$	0.05 W $m^{-2}K^{-1}$ 0.09 W $m^{-2}K^{-1}$	$U_{SKYLIGHTS}$	0.86 W $m^{-2}K^{-1}$
$U_{PARTION\ (OFFICE-OFFICE)}$	0.66 W $m^{-2}K^{-1}$	$U_{PARTION\ (OFFICE-WET\ ROOMS)}$	0.26 W $m^{-2}K^{-1}$
Shading systems	External venetian Blinds	Infiltration plus natural ventilation (Design)	0.3 ACH

HVAC SYSTEM			
In room heating and cooling terminals	Separated capillary radiant systems embodied in the external envelope (heating) and in the partitions (cooling).	Ventilation	Mechanical ventilation with heating/cooling control and heat recovery from the exhaust air. Demanded control ventilation for the meeting rooms.
Ventilation air flow	Design Value: 3600 m^3/h.	Heat Exchanger	Flat Plate, Air-to-Air, Sensible Heat
Fans Head	1002 Pa (supply), 523 Pa (Return)	$\eta_{sensible}$ = 75%	
Geothermal Heat Pump - Nominal Capacity - COP and SCOP	Water-to-water Heat Pump 27 $kW_{THERMAL}$ 5.0 W_{TH}/W_E and 3.9 W_{TH}/W_E	Cooling Generation	Passive, by means of heat exchange with the ground water (i.e., no active cooling by means of electric chillers)

PHOTOVOLTAIC SYSTEM (AS DESIGNED)			
PV Panels (66.3 kWp)	Crystalline Silicon,	Generator Efficiency	14.5%
PV Panels efficiency	≈ 17.5%	Design specific conversion	790 kWh_{ELEC}/kWp
12 Arrays Gross Area	391 m^2	Total Designed electric conversion	52461 kWh_{ELEC}
Azimuth and Tilt angles angles	8° and 10°	System Global Efficiency	13.4%

THERMAL SOLAR SYSTEM			
Gross area of Solar Collectors (Glazed, Flat Plate)	11 m^2	Thermal Storages	Sequential boilers, each one with a volume of 970 liters
Azimuth and Tilt angles	8° and 37°		

ENERGY COST, CONVERSION FACTORS AND EMISSIONS			
Electricity cost [44]	0.292 €/kWh	Electricity LCA emission factor [45]	0.706 t CO_2 / MWh

Table II – Main information of the weather file and simulation parameters

Weather Data (i.e., Reference Year)	
Weather Data	ASHRAE Berlin IWEC {GMT +1.0 Hours}
Heating Degrees-Day	3284 Kd annual (standard) (18.3°C baseline) (Official German Value for Berlin Tempelhof, G20/15: 3134)
Cooling Degrees-Day	147 Kd annual (standard) (18.3°C baseline)
Latitude and Longitude	{52° 28' North} { 13° 23' East}
Simulation Parameter	
Surface Convection Algorithm Inside	TARP – Variable Natural Convection Based on Temperature Difference
Surface Convection Algorithm Outside	DOE-2 – Correlation from measurements for rough surfaces
Heat Balance Algorithm	Conduction Transfer Function, 4 time-steps/hour
Minimum System Timestep: 1	Maximum HVAC iterations: 20
Winter Design Day	Outdoor Maximum Dry Bulb Temperature = -13.9 °C (Wet Bulb = - 13.9 °C), No solar radiation, Sky Clearness = 0, Barometric Pressure 100776.7 Pa, Wind Speed 14.1 m/s, Daily Dry-bulb Temp Range = 0°C
Summer Day in Winter	Outdoor Dry Bulb Temperature = 34.0 °C (Wet Bulb = 29.1 °C), Solar radiation from weather file, Sky Clearness = 0.98, Barometric Pressure 100776.7 Pa, Wind Speed 0 m/s, Daily Dry-bulb Temp Range = 13.4°C

Table III – Comparison between the energy demands of the designed building and simulated performances by means of EnergyPlus 7.2.0 (i.e., hourly energy simulations)

	Designed Building	Simulated Building	% GAP
Electric Energy for the space Heating (kWh/m^{2}a)	2.31	2.28	- 1.2
Electric Energy for Fans (kWh/m^{2}a)	5.93	6.04	1.9
Electric Energy for Pumps (kWh/m^{2}a)	9.14	9.03	- 1.2
Electric Energy for Artificial Lighting (kWh/m^{2}a)	10.75	10.83	0.7
Electric Energy for Office equipment (kWh/m^{2}a)	9.57	9.47	-1.0
Specific Electric Energy for the building use (no DHW) (kWh/m^{2}a)	37.7	37.65	- 0.1
Total Electric Energy for the building use (no DHW) (kWh)	44’411	44’352	- 0.1

Table IV – Calibration of the energy model: Mean Bias Errors and Coefficients of variation of the root-mean-square error

	Heating and DHW	Pumps and Fan	Lighting	Office Equipment	Total Electricity
MBE_{month}	-1.16%	0.88%	-0.67%	1.95%	1.15%
CV(RMSE)	32.50%	12.58%	17.46%	21.91%	7.96%